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VOLCANOS AND RADIOACTIVITY[1]

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One of the commonest, and perhaps the most impressive, of natural phenomena, the volcano, has hitherto been without any explanation of its cause, though it has been before the world a subject of theory for many centuries. The reason for this is quite apparent. We perceive the action of the volcano upon the surface, and we know what it does. But the theater of its origin and the development of its energy are far below the surface of the ground, out of reach of inspection or direct observation. Human ingenuity has been baffled in its efforts to explain the phenomenon because of the want of observed facts and the impossibility of obtaining them. But, while we are, and probably always shall be, unable to directly inspect the seat of origin of the volcanos, there are certain inferences in connection with them which have attained a degree of probability which entitles us to use them as facts which may limit speculation and confine it within very narrow boundaries. I purpose to mention these inferences in order to see the general nature of the solution to which they point; for, unless I am greatly mistaken, they will show us that we are close upon the verge of a solution.

1. The first fact to be mentioned is the solidity of the earth. It is so well known that I shall not dwell upon it, and merely mention it in order to bring it, together with other facts, into the same series or group.

[1] Read before the National Academy of Sciences, April 17, 1906.

2. The second fact is the comparative smallness of the extravasated masses in any single volcanic eruption. In order to obtain an idea of the relative magnitude of an erupted mass, let us draw upon a true scale, a segment of 1° of the earth's surface, of an arbitrary thickness—say thirty miles. Upon this segment draw the profile of Vesuvius. About a mile below the surface, beneath the volcano, draw the reservoir of lava, having the same mass as the volcano itself. It may have any thickness and any form, and is subject only to the condition that the capacity of it is the same as the mass of the erupted material. Now, Vesuvius is built of I know not how many individual eruptions, but let us say one hundred; though I presume that there were, in reality, very many more. A single average eruption would be the hundredth part of the volume of this reservoir. But there are eruptions known which are many times greater than the average of those of Vesuvius. The largest known in the United States are in the Snake River valley, and while we are not in a position to compute with accuracy their dimensions, we can say with confidence that the volume of the largest of them does not exceed two cubic miles. The great eruption of the Skaptar Jökul, in Iceland, in the year 1783, was estimated by Dr. Thoroddson to have outpoured twelve or thirteen cubic kilometers, or three cubic miles of lava. The greatest eruption of which we have any estimate—and that is a very crude one—was at Tomboro, on the island of Sumbawa, which was estimated to have discharged about six cubic miles of lava. This estimate is very excessive, and is probably two or three times too large.

On the same scale as before these two eruptions are represented, and you perceive how insignificant they are in mass in comparison with the whole of the surrounding earth.

3. The third general fact is the repetitive nature of volcanic eruptions. A single outbreak, with none following, is an exceeding rare phenomenon. Many eruptions, going often into the thousands, occur before the climax is reached and the decline of activity follows. The reason why a volcano, when its vent is once open, does not discharge all the material in its reservoir in one stupendous belch, and then close up forever, will be shortly brought up.

4. The next general fact, which we cannot claim to be proven, but

for which there is a growing mass of strong and highly concordant evidence, is that the seat of the reservoir is very shallow and seldom more than three miles deep. Very rarely is there any indication of its being more than two and one-half miles deep, and it is certain that in many cases the depth is less than one mile. The indications are that most of the volcanic eruptions originate at depths between one mile and two and one-half miles. The evidence of this is furnished by the earthquakes which almost always accompany them, and which are associated with them in such a way as to leave no doubt or question that they are produced by the volcanic action. The radiation of the tremors of an earthquake from their source in the earth is governed by substantially the same law as sound. The intensity of these tremors, where they reach the earth's surface, varies in a manner which is dependent upon their depth of origin. In the discussion of the Charleston earthquake I pointed out one method by which that depth can be approximately computed from the distribution of critical points of the surface intensity. The method has been sharply criticized by able seismologists as being liable to error through refraction of the rays of propagation through rocks and media of variable density. But I observe that all of them use that method with surprising consistency and satisfactory results.

The efficiency of this method depends mainly upon the accuracy with which the intensity can be estimated along a line radiating from the epicentrum. It often happens that the intensity is so much affected by the local nature of the soil and rocks that all estimates become so uncertain as to be very misleading, and all attempts to draw conclusions from them must be affected by large errors, or may fail entirely. On the other hand, in many cases the results are safer and surer than would be supposed, and we are able to give a graphic representation of the curve of intensity which must be very near the truth. In general, when an earthquake is very strong at the epicenter and quickly fades out away from it, we can say with confidence that its centrum is very shallow. If the intensity fades out slowly and the quake is felt at great distances, we can rely upon its centrum being very deep. When, therefore, we have not the means of estimating the intensity at the critical points, if we have the means of estimating the maximum intensity of the quake and of knowing how far it is felt, we can still form,

not indeed a precise or accurate estimate of its depth, but a roughly approximate one.

A qualification of the foregoing may be introduced here. The earthquake is no doubt the fracturing or sudden yielding of the rock masses immediately above the lava reservoir. We can only vaguely conjecture the distance which separates the zone of fracture from the zone of melting. But in no case could it be so great as a mile without making itself sensible in the greater depth of the quake. We must, however, increase slightly our estimate of the depth of the lava beyond the estimated depth of the quake.

We may now proceed to state the probable cause of volcanic eruptions. They are caused, I conceive, by a development of heat, resulting from radioactivity, in limited tracts at a depth of one to three —at the very utmost not over four—miles from the surface, which is sometimes sufficient to melt the rocks affected by it. The melting is gradual, and when a sufficient quantity is melted, the water which it contains becomes explosive and usually suffices to break through the covering, constituting an eruption. When all the lava is erupted, and the reservoir is exhausted, it closes up for a time. If the heat continues to be generated, more lava is melted, and in due time another eruption occurs. The process may be repeated again. It may be repeated hundreds or thousands of times. The volcanic action may continue in the same place for hundreds of thousands, or even millions, of years, or it may repeat itself only a few times, or may even occur only once. Indeed, it may fail altogether to erupt to the surface, and in many cases does fail. In other words, it goes through the entire process of preparing for an eruption and does not consummate it.

This view enables us to explain the repetitive character of volcanic eruptions, which is, perhaps, their most striking and characteristic feature. It is in strong contrast with the view long held that the lava reservoirs are a part of the original constitution of the earth, and have lain in their present position through all the vast period of the earth's evolution, waiting for a convenient occasion to explode and pour forth their fiery contents. It regards the reservoirs as having no real existence as such, and as containing no liquid eruptible contents until some source of heat acts upon them and liquefies a portion of the strata, thus giving rise to the reservoir. When a sufficient quantity of the lava is

melted to rupture its covering, the eruption follows. It continues until all the lava which exists for the time being in the reservoir is extravasated. And when all of its ammunition is expended, it must close its action until a fresh supply is provided.

By an increase of heat, we can readily understand the existence of the lava reservoirs in such anomalous positions near the surface of the earth. The horizon of melted lava, which has a temperature of about 1,000° or 1,200° C., if it depended wholly upon the secular cooling of the earth would be more than thirty miles below the surface, or even forty miles below. We cannot suppose that the cooling of the earth is so extremely unequal as to bring the isotherm of 1,000° C. at one place within two miles of the surface, and in another place carry it thirty or forty miles below. It is equally difficult to imagine any subterranean disturbance or displacement which could mechanically thrust up near the surface a portion of the solid nucleus of the earth. Such a displacement is not warranted by the geological facts; for while volcanic eruptions occur frequently in localities where the strata are much displaced, they also occur quite as often where there has been no displacement of any moment since the Cambrian age.

A singular class of phenomena is found in the so-called mud volcanos, which have always been a great puzzle, but which are easily explained by this cause. We find them in Central America and in Java, and the remarkable case of Bandai San, in Japan, is well remembered. These volcanos must have their origin at less depth than the lava eruptions. The temperature of erupted mud is not accurately known, but it cannot be less than 400° or 500° F. The generation of heat half a mile below the surface would be a sufficient explanation of their origin and action.

Why should eruptions always emanate from shallow reservoirs and never from deeper ones? Or, according to the view here put forth, why are eruptive masses formed only at depths of two or three miles, and never at greater depths? I do not contend that no lava pools are formed at greater depths than three or four miles, but if they are formed, the lava is never erupted, and for the following reason. The pressure of the overlying rock at a depth of three miles is about 18,000 pounds to the square inch. At a depth of four miles it is about 25,000 pounds to the square inch. At such a pressure (25,000 pounds) it would be im-

possible for water vapor to lift its covering and force a way to the surface, unless it had a temperature greatly exceeding 1,200° C. It would have to be heated to a considerably higher temperature to do it. But with increasing temperature the heat is conducted away more and more rapidly, until the loss of heat is equal to the quantity generated and thereafter there is no increase of temperature. The generation of radioactive heat is a slow process, and the only method of its escape is by conduction away from the radioactive source. The rate of heat generation is constant and independent of the temperature, but the rate of loss increases rapidly with the temperature. Ultimately, as the temperature rises, a point would be reached at which the loss of heat becomes equal to the gain.

If an eruption from a deep source, say five or six miles, were to occur, we should expect that the temperature of the lava would be very high—probably a white heat—and that its mass would be very great. Its consequences might be disastrous beyond all precedent.

That volcanism is caused by the generation of heat near the surface was a belief which I expressed over twenty years ago in a chapter of the work on *Hawaiian Volcanos*. Long study of the volcanic problem, in which every other theory failed and went to pieces under criticism, and this alone not only survived, but grew more probable and in accordance with the facts, led me to the hazardous step of venturing to express it. At that time no cause could be cited for the increase of heat, and the proposition met with no response—and, no doubt, justly. Geologists continued to look for the explanation of volcanoes in the gradually waning remnants of the earth's internal heat. Within the last five or six years, however, physical science has made discoveries of a wonderful nature, which open a new field—indeed, a new world—in our views of the constitution of matter, and may throw a flood of light on the very subject of our inquiry.

The subject of radioactivity is so new and so surprising that it has had time only to establish a very few of the fundamental principles which lie at the basis of it. But so hotly is the matter pursued by many of the ablest specialists that each year shows a large increase in our knowledge. As this is familiar to all physicists, I shall allude here briefly only to such as are essential to our discussion. We have to regret that some of the most fundamental questions concerning radio-

activity are as yet unsolved, though we cannot expect that a new and and far-reaching science should in six years have accomplished all of its immense possibilities.

A good many efforts have been made, by the use of the extremely sensitive quadrant electrometer, to ascertain by measurement the quantity of radioactive substances in the accessible portions of the earth. By taking samples of earth from varying depths and testing them by the electrometer, widely variable quantitative results have been obtained, but in every instance the amount of radioactivity indicated much exceeds the amount required to compensate the loss of heat from the earth by conduction and radiation into space. For instance, Professors Elster and Geitel, of Berlin, who have made many discoveries and contributed many observations in radioactivity, placed 3,300 ^{cc} of garden soil within a closed vessel with an electroscope to determine the conductivity of the inclosed gas. Allowing it to stand for several days, the conductivity of the air became constant at three times the normal amount. This increase of conductivity, Professor Rutherford estimates, would be equivalent to that produced by the emanation from 7×10^{-10} grams of radium. If the density of the soil be taken as 2, this corresponds to the emanation from 10^{-13} grams of radium per gram of clay. Now, Professor Rutherford computes that the earth's loss of heat by conduction and radiation is equivalent to what would be supplied by 4.1×10^{-14} grams of radium per cubic centimeter of its mass. According, then, to the results obtained by Elster and Geitel, twice as much heat would be supplied by radioactivity as is lost by conduction and radiation into space.

This experiment with a small quantity of soil taken up in somebody's back-yard will hardly be regarded as an accurate determination of such a quantity as the earth's supply of radioactive heat. But the question has been tested by many observers, whose results vary considerably, yet all are of the same order of magnitude. By sinking a pipe into the ground anywhere, and sucking up a sample of the air from the soil, it is found to possess a much higher degree of radioactivity than the free air at the surface. It also has a marked degree of conductivity; and this conductivity falls to half of its initial value in a little less than four days, which is regarded as proving that it is due to radium emanation. The air of caves and cellars has been observed to have a marked degree

of ionization, greatly exceeding the open atmosphere and the air in closed vessels. This is attributable only to the presence of radium emanation diffused from surrounding rocks or soils. Many common well waters give satisfactory tests of the presence of radium emanation, which is soluble in water—more so than most gases.

The most pronounced occurrence of radium is in hot springs. Their waters always give evidence of its presence, and sometimes in quantities many times exceeding the air taken from the soil or cellars. Hon. R. J. Strutt, of Trinity College, has devoted much attention to the Springs of Bath, and finds not only radium emanation in their waters, but actual radium in the deposits of the springs. The hot springs of Baden Baden have been found to contain radium salts. M. Curie has tested a large number of the mineral springs of central and southern France, and finds radium emanation in nearly all of them. Mr. Boltwood, of New Haven, has devoted considerable attention to the study of radioactivity in mineral springs, and finds that many of the waters of America contain radium emanation.

It does not appear that any extensive or systematic investigation of the emanations of active volcanoes and volcanic gases has been made. The only one I can discover is the observation of Rausch von Trauenburg on the crater of Vesuvius. The gases from that orifice produced marked ionization and a prompt discharge of the leaves of the electroscope. The subject, however, needs thorough investigation at many other volcanic vents.

The general result of the investigation, so far as it has gone, has been to make clear the fact that the amount of radioactivity in the earth much exceeds the amount which is necessary, so far as the heat generated by it is concerned, to compensate the loss of heat by conduction and radiation. In fact, it appears that the thermal condition at present is one of continual increase of internal temperature of a large portion of the earth, or is so in part, or else is one of equilibrium between loss and gain. Undoubtedly the amount of radioaction varies somewhat widely in different portions of the earth's interior, in some portions permitting a loss of heat, in others permitting a gain. And when there is a gain, it may proceed in the portions near the surface so far as to liquefy the rocks, and thus furnish all the conditions necessary to volcanic eruptions.

One of the problems at present unsolved is: Whence comes this radioactive material, and what maintains its activity? For the most part, it gives us the characteristics of radium, and in smaller degree those of thorium and uranium. The action of actinium has not yet been sufficiently pronounced to be recognized. Polonium is believed to be one of the transitional forms of radium. No other radioactive substances are yet known. The most important one thus far identified is radium. But the life and activity of radium are, from a geological standpoint, very brief. According to Professor Rutherford —and he is sustained by nearly all other physicists—radium is half consumed in a period of 1,300 years. In 13,000 years only the thousandth part of what now exists will be left, and in 26,000 years only the millionth part will remain. Quite independently of geological reasons, the belief has been that radium is generated as the product of decay of some other element, and that the amount of it in nature is sensibly constant. It is generated as rapidly as it decays. The parent element from which it may be derived is not yet decided, but there are some who suspect it to be uranium, which has immensely long life. It requires nearly 120,000,000 years to be half consumed by its own decay.

But we are not interested in pursuing and trying to test these unsolved problems. It is enough for us that radioaction exists in sufficient quantity and intensity to furnish heat enough to meet the wants of the vulcanologist.

Let us now look for a moment at the presumable details of the process. At a depth of two or three miles in the earth let us assume that radium is in process of being generated. It starts at once upon that process of transfomation of which one stage is the production of the so-called emanation, which is a gas of very high density and great penetrating power and diffusability. We know that the upper strata and soils everywhere contain it, and no reason appears why the same should not be the case with the rock beneath. Wherever the emanation penetrates, the breakup of its particles generates heat, and the temperature rises in proportion to the amount of emanation which undergoes transformation in a given time, and falls in proportion to the rate at which it is conducted away. So long as the gain of heat exceeds the loss, so long will the temperature rise until it becomes sufficient to melt the rocks.

All volcanic lavas contain water, and those whose reservoirs are near the surface contain a large amount of it Those which have a deeper origin contain a smaller amount of it. The deeper lavas are hotter, and are erupted with less violence and in greater mass, than the shallow ones, and the reason is obvious.

The foregoing is a brief abstract of a portion of a book now in preparation on volcanism.

CONDITIONS OF FOSSILIZATION[1]

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Introduction.
Superficial Consideration of Fossils.
Conditions in Which Fossils Occur.
Difficulties Encountered.
Authors' Definitions of Molds and Casts.
Definitions of Molds and Casts Followed.
Definitions of "Original," "Mold," and "Cast" Proposed.
Lithological Character of Formations, as Affecting the Preservation of Invertebrates.
General Character of Invertebrate Skeletons.
General Mineral Character of Living Invertebrates.
Replacing Minerals.
Horizon, Locality, and Lithological Character of Formations Studied.
Minerals Replacing Original Minerals Secreted by Invertebrates.

INTRODUCTION

In the study of a fossil the first important point to determine is its state of preservation—whether the fossil under consideration be the *original*, a *cast* of the original, or a *mold* of the original.

By not observing this precaution, errors have been made, and will continue to be made unless it be definitely understood what is meant by these terms and the conditions they represent in fossils.

SUPERFICIAL CONSIDERATION OF FOSSILS

A superficial consideration of a fossil is often apt to lead to a misinterpretation of its condition of preservation, for fossils vary in this respect. *Molds* may be taken for *casts*, and described as exhibiting the external structure of the original.

[1] This paper was largely prepared in 1898–99, under the direction of the late Professor Charles E. Beecher, when the writer was a graduate student at Yale, and was submitted for the degree of master of science. Its publication has been delayed because the writer wished to collect further data, which he has done in Europe and America. Another paper is in course of preparation, in which an attempt to formulate laws governing conditions of fossilization will be made.

The writer also wishes to take this opportunity to thank Professor S. L. Penfield, of Yale, for valuable suggestions during the preparation of the original manuscript.

We find the same organisms preserved in all manner of conditions, and only by a careful comparative study of the exterior and interior markings are misinterpretations to be avoided.

Fossils of the same species have been referred to different species, and the same genera to different genera. For example, *Michelinia clappii*, Hall,[1] was misinterpreted by Edwards and Haime, and referred to *Chonostegites clappii*[2] and also to *Emmonsia* (?) *cylindrica*,[3] and by Billings to *Haimeophyllum ordinatum*[4] and also to *Michelinia intermittens*.[5] (See Figs. 1, 2, 3, 4, 5, 6, 7.) This misinterpretation was due to the peculiar ways in which this genus occurs. At times the walls are coated with silica, and then filled in with calcite. At times only the siliceous coatings are left, which give a mold of the inner walls. Then again we find that they were filled with calcite, the walls having disappeared; and in this case we have a solid mold instead of a hollow one. At times the form is partly destroyed, leaving molds, casts, and parts of the original in the same specimen.

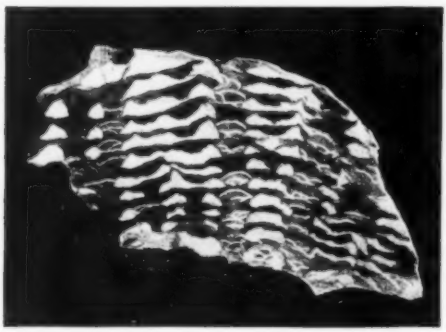

FIG. 1.—*Chonostegites clappi*. (After Edwards and Haime.)

We find fossils of the same species preserved (*a*) in their original condition, (*b*) as casts, and (*c*) as molds. In regard to the first condition little difficulty will present itself. The second and third, however, may lead to confusion, for they may not exhibit the external form.

[1] Hall, *Geology of the State of New York* (1876), "Illustrations of Devonian Fossils," Plate XVII.

[2] Edwards and Haime, Pal. Fos. d. Ten. Pal. (1851), p. 299, Plate XIV, Figs. 4, 4*a*.

[3] *Ibid.*

[4] Billings, Can. Jour. U. S., Vol. IV (1859), p. 139.

[5] *Ibid.*, p. 113.

CONDITIONS IN WHICH FOSSILS OCCUR

The following illustrations will show the various conditions in which fossils are found, and they will also serve to show the necessity for close observation and comparative study.

A. The original skeleton may be preserved. If there be hollows or spaces, they may become filled with infiltrating material. In a case of this kind little difficulty will present itself in the determination of the fossil.

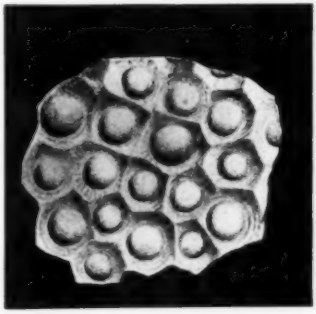

FIG. 2.—*Chonostegites clappi.* (After Edwards and Haime.)

B. The original skeleton may be replaced by some mineral and the cavities filled with the same, or some other material.

If the skeleton were composed of aragonite, and were replaced by calcite, the external form and markings would be preserved; but the internal organic structure would be lost, and hence not seen under the microscope. In this case we should depend upon external markings for identification.

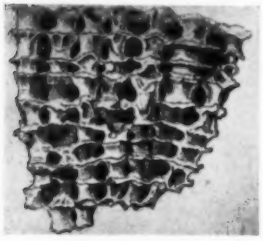

FIG. 3.—*Chonostegites clappi.* (After Miller.)

If a skeleton composed of calcite were replaced by pyrite, we could not ascertain in thin section whether the internal organic structure were lost or preserved, because of the opaqueness of the pyrite, and again we should depend upon external markings. A broken section, however, will show on the fractured surface the minutest details, in many cases.

If the organism were replaced molecularly by a mineral which transmits light, the internal organic structure would be so well preserved as to be readily distinguished under the microscope. In a case of this kind we should have a double check—the internal as well as the external structure—and its identification would be doubly sure.

C. The organism may disappear after its cavities or hollows were filled by infiltrating material. In this case we should have only the impression of the interior of the original, and it would be necessary to compare this with the interior of skeletons already known. This is at times difficult; but it is the only alternative. To make this comparison it might be necessary to take an impression, or *cast*, from the *exterior* of this filling, which cast would show the markings of the *interior* of the original. Unless we could find a fossil or a

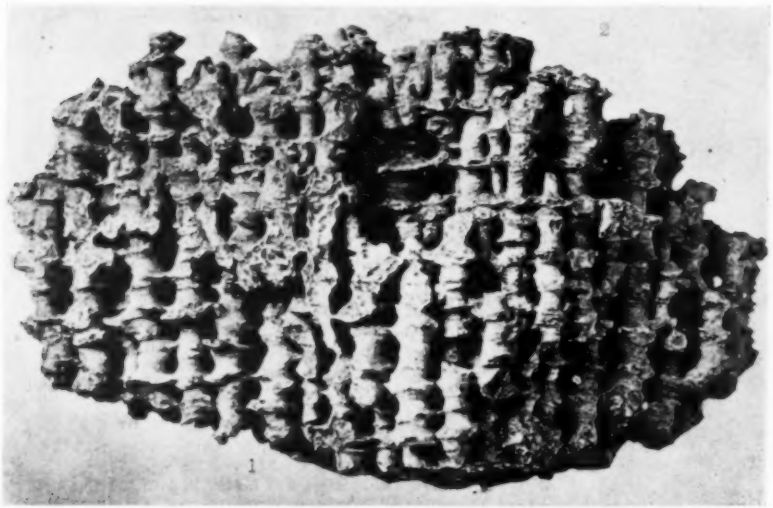

FIG. 4.—*Michelinia clappi*. (After Hall.)

living form showing the same, or nearly the same, internal markings, we should be baffled in any attempt to adjust it to its zoölogical position, and hence its identification would remain unsolved until one of these two conditions was satisfied.

D. The hard parts of an organism may leave only an impression of its exterior in the matrix. It will then be necessary to take an impression, or *cast*, from this first impression, or *mold*, and upon the markings shown on this cast will depend the identification of the fossil.

E. The exterior of the skeleton may become coated with some mineral such as silica, after which the skeleton may disappear. In this case we should have a hollow mold. It would then be necessary to take an impression, or cast, from this mold in order to ascertain the external markings of the original, and by comparing this cast with known forms we can determine its identity. At times the corallites in a compound coral will become coated with silica, and the spaces between the corallites filled with calcareous material

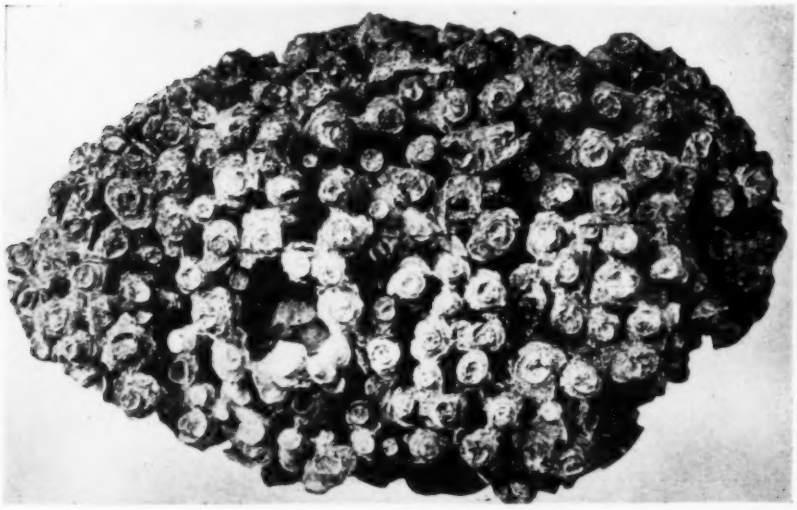

FIG. 5.—*Michelinia clappi.* (After Hall.)

the entire corallum having disappeared, leaving a mass filled with these hollow siliceous tubes, the inner surfaces of which will be molds of the exteriors of the corallites. (See *Michelinia*, previously referred to.)

We may have the exterior coated with silica, the skeleton then disappearing, and the space left filled with calcite. In a case of this kind we have molds of the exterior, and it is impossible to identify the fossil without first dissolving out the calcite, after which the procedure will be as already described.

The interior cavities or hollows of a coral may become coated with silica, after which the skeleton may disappear, leaving molds of the *interior* which will have the appearance of a sponge. If we had a coating which had been deposited upon the inner surface of the shell, it might be easily determined by taking a cast for comparison with other shells; but in the former case its identification would be extremely difficult, for we might not be able to secure casts from these molds. Even if this could be done, we might still have difficulty in its identification, for we should have only casts of the interior of the cavities or hollows of the original for comparison.

DIFFICULTIES ENCOUNTERED

From the foregoing it is plain that difficulties present themselves even when it is known that the fossil in hand is the *original*, a *mold*, or a *cast;* but the difficulties increase if it be not known what the condition of preservation is. Cases present themselves in which it is a very difficult matter to decide whether the fossil is a cast or a mold; but in the majority of cases this difficulty is obviated by close observation and an understanding of the meaning of *casts* and *molds*.

It is only by a study of casts and molds in their various conditions—found as fossils or made in the laboratory—that we may with a certain degree of exactness determine the condition of preservation of a fossil. The internal markings of some forms resemble the external markings of other forms, and it is only in the above way that we may be certain that we are dealing with external or internal markings.

There is a wide difference between a cast and a mold. Ca ts vary in that some do and some do not show the structure of the organism. *Receptaculites oweni*, Hall, from the Galena (Lower Silurian) at McGregor, Iowa, represents the inner surface of the skeleton, and is a cast. (See Figs. 1 and 8.) "In most specimens . . . . the remains consist of the filling of the intermural space, with casts of the outer surface of the inner wall, the inner surface of the outer wall, and of the connecting tubes."[1] This is a calcite

[1] Bernard, *Principles of Paleontology*, Fourteenth Annual Report, New York Geology (1895), pp. 89, 90.

cast of the interior, and has been regarded as having the structure of the original organism. The conditions were evidently such as to preclude its preservation in its original condition, or in such a condition as to render its determination certain.

AUTHORS' DEFINITIONS OF MOLDS AND CASTS

Authors differ in their definitions of molds and casts. Some make the terms synonymous. Others define them separately, but are not consistent in their application.

Darwin[1] considers the *mold* as a matrix, and the impression made by an organism in this matrix he terms a "cast."

Bernard[2] applies the term "mold" to three distinct results: (*a*) to an impression made by the exterior or the interior of a shell; (*b*) to molecularly replaced organisms; and (*c*) to fillings of impressions.

Gratacap[3] applies the term "cast" to (*a*) fillings which take the place of organisms, to (*b*) the material filling the space occupied by the soft parts. The term "mould" he applies to impressions of the exterior of an organism.

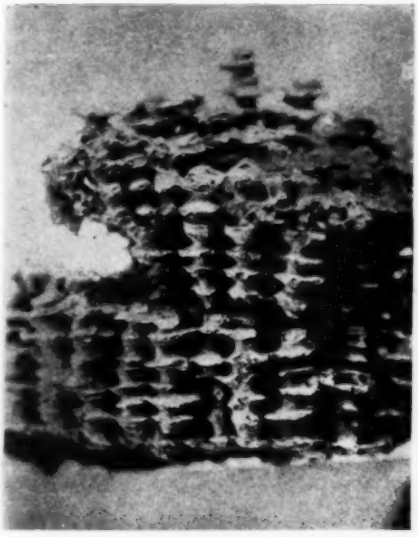

FIG. 6.—*Michelinia clappi*. (After Rominger.)

White[4] applies the term "mold" to impressions made by the organism. To the material filling this "mold" he applies the

[1] Darwin, *Geological Observations*, Vol. II, p. 414.

[2] Bernard, *op. cit.*

[3] Gratacap, "Fossils and Fossilization, *American Naturalist*, Vols. XXX, XXXI, pp. 288, 902, 903.

[4] White, Con. of Pres. of Inver. Fos., Bull. U. S. G. & G. S., Vol. V, No. 1, p. 135.

term "cast." He[1] also uses the term "histometabasis" for the condition which produces a molecular replacement or substitution or paramorphism.[2] He uses the term "fossil pseudomorphs" for the materials occupying cavities formerly occupied by shells, the occupation having taken place by precipitation due to infiltration. He uses the term "fossil molds" for "cavities in sedimentary rocks which were originally occupied by fossils," and says that "the original surface features and markings are often minutely preserved in molds." He also uses the term "casts" for "counter-parts of fossils," and also for the material which may occupy the animal chamber. He further speaks of making "artificial casts of natural molds" in order to get "the original form and surface features."

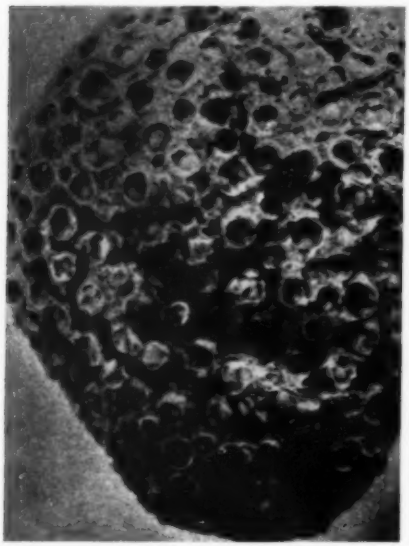

FIG. 7.—*Michelinia clappi.* (After Rominger.)

Geikie[3] applies the term "mold" to impressions made by the organism. To the material filling this "mold" he applies the term "cast." He[4] also applies the term "cast" to the material occupying the animal chamber.

Von Zittel[5] applies the term "mold" to impressions. The term "cast" he applies to the material which occupies the "interior of a shell or hollow body."

[1] White, "Relation of Biological and Geological Investigations, *Proceedings of the* U. S. *N. M.*, Vol. XV, pp. 264–67.

[2] Dana, *Text-Book of Mineralogy*, (1898), p. 293.

[3] Geikie, *Text-Book of Geology*, 3d ed., p. 651.

[4] Geikie, *Outlines of Field-Geology*, 5th ed., p. 78, Fig. 14.

[5] Von Zittel, *Text-Book of Palaeontology*, Eastman translation, Vol. I, Part 1, p. 2.

Woods[1] applies the term "mold" to (*a*) the impression, to (*b*) the material filling the space occupied by the animal. The term "cast" he applies to (*a*) the material filling the space occupied by the organism, and to (*b*) the material filling the internal cavity or cavities.

Nicholson and Lydekker[2] use the terms "mold" and "cast" interchangeably.

Lyell[3] applies the term "mold" to the matrix in which an impression of the exterior has been made. The term "cast" he applies

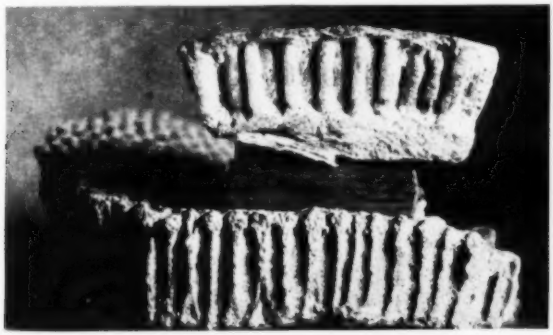

FIG. 8.—*Receptaculites oweni*, Hall. (From specimens in Yale Museum.)

to (*a*) the material filling the interior of the organism, and to (*b*) the material filling the space left by the organism.

Penning[4] uses the term "unchanged fossils" for unaltered shells or valves, or those which have lost only the animal matter. "Replaced fossils" he applies to the material which has been substituted for original material of the shell. "Internal cast" he uses for "the impression or *reversed facsimile of the external form of the organism*[5] that once filled the empty space" of the shell. The term "external cast" he uses for impressions made by the exterior of the shell, and says that "by taking an artificial cast from the

[1] Woods, *Palaeontology*, 2d ed., pp. 6, 7.

[2] Nicholson and Lydekker, *Manual of Palaeontology*, 3d ed., Vol. I, pp. 5, 6.

[3] Lyell, *Students' Elements of Geology*, 3d ed., pp. 42–46.

[4] Penning, *Text-Book of Field-Geology*, 2d ed., pp. 208–12, and Fig. 29, p. 211.

[5] The writer's italics.

external impression" we obtain "an accurate representation of the pre-existing shell."

Williams[1] is perplexing in his use of the terms "mold" and "cast." He says:

> Thus a fossil . . . . may consist of the shell now removed, in which case it may be the reverse or cavity over the exterior of the shell, or . . . . similar impressions of the inner surface; or the cavity may be again filled with detrital matter, forming a cast of either the inner or outer form of the shell or object fossilized; in the former case it would be called a mold; in the latter, a cast.

Schuchert[2] applies the term "mold" to impressions of the exterior and speaks of the mold as "preserving the exterior form and ornamentation" of the shell. He is ambiguous in his use of the term "cast" for he may be referring to a matrix which contains concave impressions (impressions of the exterior of a valve) or convex impressions (impressions of the interior of a valve), or to the material which replaces a valve.

DEFINITIONS OF "MOLDS" AND "CASTS" FOLLOWED

The definitions followed in this paper are the following: A *mold* is "a form or model pattern of a particular shape, used in determining the shape of something in a molten, plastic, or otherwise yielding, state." "In founding, a *mold* is the form into which a fused metal is run to obtain a *cast*."[3]

The *mold* determines the shape of the material put in or upon it, and this material, when removed, will be an exact duplicate of the object from which the mold was made. This removable material is termed a *cast*. The depressions in the original object will appear as protuberances in the mold, and the protuberances as depressions. The cast will show the depressions and protuberances as they appear in the original.

The surface of the original object upon or around which the mold is made may be either convex or concave. If it be concave, the mold will be convex, and *vice versa*. A mold with a convex surface is called by some authors a "cast." If the skeletal part

[1] Williams, *Geological Biology* (1895), p. 79.

[2] Schuchert, "Directions for Collecting Fossils," Part k, *Bulletin No.* 39, U. S. N. M., p. 13.

[3] *Century Dictionary*, "Mold."

of an organism be hollow or has a concavity, this space is considered a "mold" from which a "cast" is taken. This is obviously wrong, for in this case the "mold" is the *object*, and the "cast" the *mold* from which a *cast* may be taken, and *this* cast will be a duplicate of the object.

Then, again, an impression from a convex object is termed by some a "cast." This is also obviously wrong, for the "cast" would have the markings of the object in reverse order; hence it would be a mold.

The general concavity or convexity of a surface will not determine it as a mold or a cast. Such determinations depend upon the markings of that surface.

DEFINITIONS OF "ORIGINAL," "MOLD," AND "CAST" PROPOSED.

In attempting to fix the meaning of the terms "original," "mold," and "cast," it is hoped the following definitions will prove acceptable, especially the latter two:

I. The term *original* is used to designate an organism[1] that has not lost its original structure or composition, to any appreciable extent, in the process of fossilization, except the organic matter which may have filled the interstitial spaces. (See Fig. 9 *a* and *b*.)

FIG. 9.—(*a* and *b*) originals; (*c*) mold of interior.

II. The term *mold* is used to designate the imprint of the exterior or interior of an organism. (*a*) If the organism leave an imprint of the exterior, this imprint is a *mold of the exterior*. (See Fig. 10.) (*b*) If the hollow organism become filled with material this material

[1] Strictly speaking, a lifeless animal is not an organism; but in common parlance the lifeless body is an organism because it is that which at one time functioned. Likewise, we speak of the products of life as organic. Therefore, for lack of a beter term, *organism* is used to denote the harder parts of animals which we term *fossils*, the softer or destructible parts of which have decayed and passed away. The term "organism" can in no sense, however, be applied to molds and casts, although these are fossils as much as the unaltered skeletal parts of animals.

is a *mold of the interior.* (See Figs. 9*c*, 11, 12.) (*c*) It follows from the above that, if the hollow organism become filled with and imbedded in material of the same, or different, composition, and then disappears, we have left a mold of the exterior in the matrix and a mold of the interior in the form of a kernel. (See Figs. 9*c*, 10.)

FIG. 10.—Mold of the exterior.

III. The term *cast* is used to designate the material which takes the place of the *original*, whether by replacement due to a molecular process or to infiltration. It is also used to designate the material occupying the mold made by the exterior or interior. (See Figs. 10, 12, 13, 14.)

If the mold described under II (*a*) becomes filled, we have a cast of the exterior. If the mold described under (*b*) becomes imbedded, its imprint will be a cast of the interior. If the space between the two molds described under (*c*) becomes filled, we have a cast of the exterior and interior, and therefore an object the same in shape and outline as the original. If the original be gradually replaced molecularly by some mineral, we have a cast which will show its shape, outline, and internal structure.

FIG. 11.—Mold of the interior.

From the foregoing it is obvious that an *original* is the organism itself; a *mold*, the reverse of the *original;* and a *cast*, the counterpart of the *original.* The latter may or may not show the internal organic structure.

It follows, therefore, that the only way one may know whether the markings on certain molds or casts represent the exterior or

interior of known forms is, as has been previously said, to make a study of molds and casts, and thus reduce the liability of mistakes to a minimum.

THE LITHOLOGICAL CHARACTER OF FORMATIONS AS AFFECTING THE PRESERVATION OF INVERTEBRATES

The conversion of an organism into a fossil depends upon the character of its skeletal parts, the material in which it is buried, and the material brought in, in solution, by infiltration. The material of which the skeletal part is composed varies in different groups, being more durable in some than in others, and therefore plays an important part in the preservation of the organism. The variation in the lithological character of the material in which the organism is buried also plays an important part in its preservation. Certain organisms are preserved as originals; others as molds and casts, in the same formation and locality. In this same formation, but in a locality of different lithological character, those groups which were lost under the former condition may be retained under the latter, and *vice versa*.

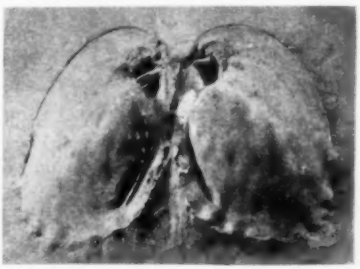

FIG. 12.—Mold of the interior.

Apparently a law could be formulated to the effect that organisms of the same mineral composition will be preserved in the same manner, as originals, molds, or casts. In reality, however, this is not true. Organisms are more completely preserved as originals in limestone; yet it is in limestone that we find the most casts by molecular replacement. Molds and casts are very common in sandstones. As limestone approaches dolomite, the molds and casts increase, although we also find originals. We find molds in hematite; but they are more rare than in sandstones.

The most perfect fossils are found in sandy and clayey shales. The Niagara group at Waldron, Ind., is made up of fine calcareous shales which are overlain by limestone. In these shales we find

quantities of corals, bryozoans, and crinoids. The brachiopods are more or less preserved as originals. The sponges, gastropods, annelids, and crustaceans are well represented. The lamellibranchs and cephalopods, however, are absent.

The Paleozoic hexactinellids occur in groups of strata containing other organisms; but in their own particular beds the absence of other forms is striking. In Steuben county, N. Y., the formation is a sandstone which is fine-grained and argillaceous, and contains very few crinoids and brachiopods; but *Hydnoceras tuberosum* occurs in abundance.[1]

FIG. 13.—Cast of the exterior.

The fossils in the sandy and gravelly deposits of the Potsdam, the Medina, the Chemung, the Catskill, the coarse conglomerates of the Lower Carboniferous, or the calcareous grit of the Schoharie and Oriskany, all show different conditions of preservation.

The trilobites in the Potsdam of Wisconsin and Minnesota are badly broken up. In the Cambrian of Wisconsin we find argillaceous layers in which are molds and casts. The Medina sandstone contains poorly preserved fossils, and shows molds of the interior.

FIG. 14.—Cast of the interior.

In the calcareous sandstones of the Chemung we find well-preserved organisms; but in the Catskill sandstones they are poorly preserved.

The Utica, Marcellus, and Genessee slates show well-preserved originals; but the majority of the fossils are molds.

[1] Beecher, *Memoirs of the Peabody Museum*, Yale University, Vol. II, Part 1.

The articulate Brachiopoda, the Anthozoa, and the Bryozoa of the New York Hamilton Shales are well preserved; but the Mollusca occur as molds and casts. Trilobites, inarticulate brachiopods, and ostrocods are well preserved. In the Carboniferous shales of Illinois the Mollusca are well preserved.

In the Mesozoic sandstones of the West the fossils are casts and molds generally, with the exception of the Ostrea and allied genera.

The best fossils, as a rule, are found in those limestones which contain more or less argillaceous or siliceous ingredients, as in the Waldron beds of Indiana, the Hamilton layers of New York, and the Lower Carboniferous of Crawfordsville, Ind.

The Schoharie grit, the Oriskany sandstone, and the Calciferous beds along Lake Champlain give siliceous molds on weathering.

The Upper Helderberg limestone gives molds and casts better than sandy deposits in general. At Cumberland, Md., however, the brachiopods are perfectly preserved as casts of silica in the Oriskany sandstone.

In the Galena limestone many of the fossils are preserved as casts composed of galena. The coal-measures show molds coated with pyrite. In the Clinton of Oneida County, N. Y., we find limonite casts. In the Trenton of Wisconsin and Tennessee we find casts of silica. In the Niagara limestone of western New York we find calcite casts; but on the weathered surfaces they are siliceous. In the Schoharie grit we find siliceous molds of the interior of brachiopods.

In general, calcareous skeletal parts show an unequal persistence as fossils in their original condition. Chitinous skeletons are never preserved in their original condition.

GENERAL CHARACTER OF INVERTEBRATE SKELETONS

Chitin is confined to the Arthropoda and a few brachiopods which are made up of alternating layers of phosphate of lime and chitinous material, as in *Lingula anatina* and in the graptolites.

Silica is confined to the arenaceous Foraminifera, the Radiolaria, the Silicispongia, and Diatoms.

Calcareous material is confined to the porcellaneous and vitreous

TABLE I

HORIZON, LOCALITY, AND LITHOLOGICAL CHARACTER OF FORMATIONS, AND THE CONDITION OF PRESERVATION OF CLASSES, STUDIED

Horizon	Locality	Lithological Character	Class	Condition of Preservation	Remarks
Carboniferous	Yellow Cr., Ohio	Shale	Brachiopoda	O M*	M exterior and interior
Subcarboniferous	Crawfordsville, Ind.	Limestone	Spongiae	C	Pyrite
	Mazon Cr., Ill.	Limestone	Arachnide	M C	Exterior
	Burlington, Ia.	Limestone	Anthozoa	C	Silica
			Crinoidea	C	Calcite, silica
			Brachiopoda	O C	C siliceous
(Waverly)	Warren, Pa.	Sandstone	Anthozoa	C	Exterior, sandstone
			Crinoidea	M	Heads and arms, sandstone
			Ophiuroidea	M	Exterior, sandstone
			Brachiopoda	O M C	M exterior and interior, silica; exterior, sandstone; interior, sandstone, calcite. C exterior, silica
			Lamellibranchiata	O	Slightly changed
			Gastropoda	M	Exterior, sandstone
			Cephalopoda	M C	Sandstone
(Chester, top of)	Pulaski Co., Ky.	Limestone	Bryozoa	O	Slightly changed
(St. Louis Upper)	Breckenridge Co., Ky.	Limestone	Anthozoa	C	Silica
			Brachiopoda	O	Slightly changed
	Mt. Vernon, Rockcastle Co., Ky.	Limestone	Brachiopoda	C	Exterior, silica
			Gastropoda	C	Silica
(St. Louis)	Taylor Co., Ky.	Limestone	Anthozoa	C	Silica
			Brachiopoda	C	Silica
	Scaffold Cone Ridge, Madison Co., Ky.	Limestone	Anthozoa	C	Silica
			Brachiopoda	C	Silica
(Keokuk)	Russellville, Ky.	Limestone	Blastoidea	C	Silica
	Kings Mt., Lincoln Co., Ky.	Limestone	Anthozoa	O	Spaces filled with calcite
	Keokuk, Ia.	Shale	Anthozoa	O	Spaces filled with calcite
			Crinoidea	C	Silica
					Calcite
			Bryozoa	M C	Calcite
			Brachiopoda	C	Exterior, silica, calcite
			Gastropoda	C	Calcite
			Trilobita	C	Exterior, calcite
(Burlington, Upper)	Burlington, Ia.	Shale	Crinoidea	C	Calcite
Devonian, Upper (Genesee)	Livingston Co., N. Y.	Slate	Brachiopoda	O C	O slightly carbonized
					C exterior, pyrite
			Pteropoda	C	Slate
(Chemung)	Cohocton, N. Y.	Sandstone	Spongiae	M C	M exterior, argillaceous sand; C sandstone
	Loan Valley, N. Y.	Shale	Anthozoa	O	Slightly changed
			Crinoidea	C	Calcite
			Brachiopoda	O	Slightly changed
Devonian, Middle (Hamilton)	Widder, Can.	Shale	Anthozoa	O	Spaces filled with calcite
			Brachiopoda	O	Spiralia pyrite; in some cases absent; shell filled with calcite and at times with mud
	Geneseo, N. Y.	Shale	Anthoza	C	Calcite; spaces filled with same

*O—original; M—mold; C—cast.

TABLE I.—*Continued*

Horizon	Locality	Lithological Character	Class	Condition of Preservation	Remarks
Devonian, Middle (Hamilton) —*Continued*			Crinoidea	C	Exterior, calcareous
			Bryozoa	C	Calcite
			Brachiopoda	O M C	M and C calcite
			Lamellibranchiata	O C	C exterior
			Gastropoda	C	Exterior and interior in mud; of original in mud
			Cephalopoda	C	Calcite; spaces filled with same
			Trilobita	M C	Exterior
	Pratts Falls, N. Y.	Shale	Brachiopoda	O M C	M in shale; C calcite
			Gastropoda	C	Calcite
			Cephalopoda	C	Calcite
	E. Bethany, N. Y.	Shale	Anthozoa	C	Calcite
			Brachiopoda	O	Slightly changed
			Gastropoda	O M	O slightly changed; M of exterior
	Michigan	Limestone	Hydrozoa	C	Replacement; spaces filled with calcite
	Thunder Bay, Mich.	Limestone	Anthozoa	M C	Both siliceous; C calcite
			Hydrozoa	M C	M siliceous; C calcite
			Crinoidea	C	Siliceous
			Bryozoa	M C	M siliceous; C calcite
			Brachiopoda	O M C	O slightly changed; C siliceous and calcite; M exterior and interior
			Cephalopoda	C	Siliceous
Devonian, Lower (Corniferous)	Columbus, Ohio	Limestone	Anthozoa	C	Calcite and spaces filled with same; silica, and spaces filled with same; also partly calcite and silica; calcite in matrix, but weather out silica
			Brachiopoda	O M C	M and C calcite: M exterior, silica, and also calcite
			Gastropoda	M	Interior, calcite
			Cephalopoda	C	Calcite
			Trilobita	M	Exterior, silica
	Jeffersonville, Ind.	Limestone	Anthozoa	C	Calcite
			Crinoidea	C	Calcite
			Bryozoa	C	Calcareous
			Brachiopoda	C	Calcite, also calcareous
	Charleston, Ind.	Limestone	Anthozoa	C	Calcite; Silica
			Crinoidea	C	Siliceous
			Brachiopoda	C	Siliceous
Silurian, Upper (Lower Helderberg)	Albany Co., N. Y.	Limestone (Shaley)	Anthozoa	C	Silica
			Bryozoa	C	Silica
			Brachiopoda	C	Silica
			Ostrocoda	C	Silica
			Trilobita	C	Silica
		Limestone	Trilobita	O M C	O slightly changed; M interior calcareous, exterior limestone; exterior and interior limestone; also clay; C exterior silica; interior silica
		Waterlime	Anthozoa	C	Silica
		Limestone	Brachiopoda	O M C	O slightly changed; M exterior silica; C carbonized
			Pteropoda	C	Exterior, limestone
			Merostomata	M C	M exterior; shields and segments of abdomen; C carbonized
	Albany, N. Y.	Siliceous Limestone	Anthozoa	C	Siliceous
			Bryozoa	C	Siliceous
			Brachiopoda	C	Siliceous

TABLE I.—*Continued*

Horizon	Locality	Lithological Character	Class	Condition of Preservation		Remarks
Silurian, Upper (Lower Helderberg) —*Continued*	Jerusalem Hill, Herkimer Co., N. Y.	Waterlime Limestone	Crinoidea	O	C	O slightly changed; C stems, calcite
	Cedarville, Herkimer Co., N. Y.	Limestone	Anthozoa		C	Calcite; silica
			Brachiopoda	O	C	C calcareous; siliceous
			Gastropoda		C	Exterior, calcareous
			Trilobita	O		Tests of pygidium slightly changed
	Indian Ladder, Albany Co., N. Y.	Limestone	Spongiae		C	Siliceous
						Calcareous
			Anthozoa		C	Siliceous
			Crinoidea		C	Ring formed of silica and filled with calcite
			Bryozoa		C	Siliceous
			Brachiopoda		C	Siliceous
(Niagara)	Lockport, N. Y.		Anthozoa		C	Silica; calcite
			Crinoidea		C	Calcite
			Brachiopoda	O		Slightly changed
			Crustacea	O		Tests; slightly changed
	Charleston, Ind.	Siliceous Limestone	Anthozoa		C	Calcite; silica
			Crinoidea		C	Siliceous
			Brachiopoda		C	Siliceous
Silurian, Lower (Hudson River)	New York	Shale	Graptolitoidea		C	Carbonized
	Cincinnati, O.	Limestone	Anthozoa		C	Calcite
			Brachiopoda	O		Slightly changed
			Cephalopoda		C	Calcite
(Lower Hudson)	Clarksville, N. Y.	Shale	Spongiae	M	C	M arenaceous; pyrite; manganese; C spicules replaced by silica and canals filled with calcite
	Franklin Co., Ky.	Shale	Spongiae		C	Spicules and walls of canals of silica; also calcite; canals filled with chert
(Trenton)	Kentucky	Limestone	Spongiæ		C	Silica

Foraminifera, the Cœlenterates, except the Silicispongia, the Echinodermata, some of the Vermes, the Molluscoidea, and the Mollusca.

Chitin undergoes more or less alteration. In some cases it is replaced by calcite.

Silica secreted by organisms is dissolved with comparative ease. It is at times replaced by calcite. The siliceous sponges are very commonly replaced by calcite. If a siliceous organism be found as a siliceous fossil, the original silica has probably been either altered or replaced by silica.

Carbonate of lime is easily dissolved. It is made use of in two forms by organisms. In the form of calcite it is more durable than in the form of aragonite. This is due to the differences in compactibility, hardness, and specific gravity. Gastropods, many lamellibranchs, corals, and other organisms composed of aragonite crumble down and pass into calcite, or disappear, while many composed

of calcite may remain. In some strata the aragonite skeletons have entirely disappeared. This is most likely to occur in pervious beds. The presence of calcite forms does not necessarily imply that they were not associated with aragonite forms. The conditions of preservation also vary. In the Mesozoic clays we find cephalopods as originals, while in the Palaeozoic clays they are calcite casts. *Mytilus edulis* secretes aragonite as its inner layer and calcite as its outer layer. Fossils occur in which the inner layer is gone. Calcite replaces aragonite at times; but in such cases the internal organic structure is gone. As yet no example of aragonite replacing calcite has been reported.

Under Table I is given the horizon, locality, and lithological character of the formations studied, and also the class, conditions of preservation, and remarks in connection with certain forms found in these formations.

GENERAL MINERAL CHARACTER OF LIVING INVERTEBRATES

Foraminifera.—The vitreous and porcellanous forms are calcite. The arenaceous forms are siliceous throughout, or have a sandy-siliceous layer incrusting an interior calcareous layer. The *Gromidae* are chitinous.

Radiolaria.—Some are composed of acanthine and some of silica.

Spongiae.—The *Myxospongiae* are composed entirely of soft tissues. The *Ceratospongiae* are made up of spongin fibers. The *Silicispongiae* are made up of siliceous elements or contain siliceous spicules. The *Calcispongiae* contain calcareous spicules.

Anthozoa.—The *Madreporaria* are aragonite, and the *Alcyonaria* are calcite.

Hydrozoa.—The *Hydrocorallinae* are calcite (?) and the *Tubulariae* calcite (?) and chitin. The *Graptolitoidea* are chitin.

Echinodermata.—Calcite.

Vermes.—Calcite (?).

Bryozoa.—Calcite and aragonite (?).

Brachiopoda.—Calcite.

Lamellibranchiata.—Some are calcite, some aragonite, and some both calcite and aragonite in layers.

Scaphopoda.—Aragonite (?).

Gastropoda.—Aragonite. Some are composed of aragonite and calcite.

Cephalopoda.—Mainly aragonite. *Nautilus pompilius* has calcite for its inner layer and septum, instead of aragonite as heretofore reported.

Crustacea.—Mainly calcite.

REPLACING MINERALS

The hard parts of invertebrate organisms are composed of more or less soluble mineral matter, and are often replaced by other minerals which fill the cavities left by the hard parts. There may be molecular replacement as the original gradually disappears, or the cavity may be filled by precipitation after the original has entirely disappeared. Chemical reaction may take place, producing new minerals as the elements in the original unite with the elements in the matrix, or elements brought in due to the porosity of the imbedding material.

The imbedding material always contains minerals that are easily dissolved under such conditions as heat, pressure, and moisture, and they may be deposited separately or in combination. The predominating mineral is apt to be found forming molds or casts of the lost parts.

In calcareous shales we find calcite casts. In siliceous limestones we find siliceous casts. In ferruginous formations we find siderite, pyrite, limonite, etc., casts and molds. In galena-bearing formations we find casts composed of that sulphide. These illustrations might be extended; but they suffice to show how the character of a formation affects an original skeletal part in its preservation.

The most common replacing minerals are calcite, pyrite, silica, limonite, sphalerite, vivianite, barite, malachite, siderite, and hematite. The list of replacing minerals is quite large, thirty-five being the number. Others undoubtedly occur, and sooner or later will be added to our present list. Under Table II is given the replacing minerals found, and their symbols, Dana's system being followed in their classification.

In the paper to follow will be given a table showing the mineral composition of the more closely related living and fossil forms studied.

TABLE II

MINERALS REPLACING MINERALS SECRETED BY INVERTEBRATES[1]

CARBONATES, ANHYDROUS: Calcite ($CaCO_3$), Cerussite ($PbCO_3$), Magnesite ($MgCO_3$), Siderite ($FeCO_3$), Smithsonite ($ZnCO_3$).
CARBONATES, BASIC HYDROUS: Malachite ($CuCO_3.Cu(OH)_2$).
CHLORIDES, ANHYDROUS: Cerargyrite (AgCl).
FLUORIDES, ANHYDROUS: Fluorite (CaF_2).
METALS: Copper (Cu), Silver (Ag).
NON-METALS: Sulphur (S).
OXIDES, ANHYDROUS: Cassiterite (SnO_2).
OXIDES, HYDROUS: Limonite ($2Fe_2O_3.3H_2O$), Psilomelane (H_4MnO_5 (?).
OXIDES, SESQUI: Hematite (Fe_2O_3).
PHOSPHATES, ANHYDROUS: APATITE ($(CaF)Ca_4P_3O_{12}$).
PHOSPHATES, HYDROUS; Vivianite ($Fe_3P_2O_8$).
SULPHATES, ANHYDROUS: Barite ($BaSO_4$), Celestite ($SrSO_4$), Anglesite ($PbSO_4$).
SULPHATES, HYDROUS: Gypsum ($CaSO_4.2H_2O$).
SULPHIDES, DI: Pyrite (FeS_2), Marcasite (FeS_2).
SULPHIDES, MONO: Sphalerite (ZnS), Galena (PbS), Chalcocite (Cu_2S), Cinnabar (HgS).
SILICATES, HYDROUS: Kaolinite ($H_4Al_2Si_2O_4$), Gümbelite ($SiO_2.Al_2O_3.Fe_2O_3.MgO.K_2O.Na_2O.H_2O$), Glauconite (Hydrous silicate of Fe and K), Margarite ($H_2CaCl_4Si_2O_{12}$).
SILICATES, SUB: Calamine ($H_2Zn_2SiO_5$).
SILICON, OXIDES OF: Flint (SiO_2), Silica (Sio_2), Sand (SiO_2).

REFERENCES TABLE II

BERNHARD, *Éléments de Paléontologie*, 1895.
GEIKIE, *Text-Book of Geology*, 3d ed., 1893.
GRATACAP, *American Naturalist*, Vol. XXXI, No 363.
NICHOLSON and LYDEKKER, *Manual of Paleontology*, 3d ed., Vol. I, 1889.
REIS, "Ueber Petrifikation der Muskel," *Archiv für mikroskopische Anatomie*, Vol. XLI.
TRABUCCO, *La Petrificazione*, 1887.
VON ZITTEL, *Handbuch der Paläontologie*.
WHITE, *Bulletin of the United States Geological Survey*, Vol. I, No. I, Art. 8, 1879.
———*Bulletin of the United States Geological and Geographical Survey of the Territories*, Vol. V, 1880.

[1] The writer is indebted to the late Professor Beecher for valuable material from his private collection; to Rt. Rev. Joseph C. Hartzell, Bishop of Africa, for material from that continent; to Rev. Morton Culver Hartzell, for material from Germany; and to Major Ebenezer Thresher, for material from France.

Gastropoda.—Aragonite. Some are composed of aragonite and calcite.

Cephalopoda.—Mainly aragonite. *Nautilus pompilius* has calcite for its inner layer and septum, instead of aragonite as heretofore reported.

Crustacea.—Mainly calcite.

REPLACING MINERALS

The hard parts of invertebrate organisms are composed of more or less soluble mineral matter, and are often replaced by other minerals which fill the cavities left by the hard parts. There may be molecular replacement as the original gradually disappears, or the cavity may be filled by precipitation after the original has entirely disappeared. Chemical reaction may take place, producing new minerals as the elements in the original unite with the elements in the matrix, or elements brought in due to the porosity of the imbedding material.

The imbedding material always contains minerals that are easily dissolved under such conditions as heat, pressure, and moisture, and they may be deposited separately or in combination. The predominating mineral is apt to be found forming molds or casts of the lost parts.

In calcareous shales we find calcite casts. In siliceous limestones we find siliceous casts. In ferruginous formations we find siderite, pyrite, limonite, etc., casts and molds. In galena-bearing formations we find casts composed of that sulphide. These illustrations might be extended; but they suffice to show how the character of a formation affects an original skeletal part in its preservation.

The most common replacing minerals are calcite, pyrite, silica, limonite, sphalerite, vivianite, barite, malachite, siderite, and hematite. The list of replacing minerals is quite large, thirty-five being the number. Others undoubtedly occur, and sooner or later will be added to our present list. Under Table II is given the replacing minerals found, and their symbols, Dana's system being followed in their classification.

In the paper to follow will be given a table showing the mineral composition of the more closely related living and fossil forms studied.

TABLE II

MINERALS REPLACING MINERALS SECRETED BY INVERTEBRATES[1]

CARBONATES, ANHYDROUS: Calcite ($CaCO_3$), Cerussite ($PbCO_3$), Magnesite ($MgCO_3$), Siderite ($FeCO_3$), Smithsonite ($ZnCO_3$).

CARBONATES, BASIC HYDROUS: Malachite ($CuCO_3.Cu(OH)_2$).

CHLORIDES, ANHYDROUS: Cerargyrite (AgCl).

FLUORIDES, ANHYDROUS: Fluorite (CaF_2).

METALS: Copper (Cu), Silver (Ag).

NON-METALS: Sulphur (S).

OXIDES, ANHYDROUS: Cassiterite (SnO_2).

OXIDES, HYDROUS: Limonite ($2Fe_2O_3.3H_2O$), Psilomelane (H_4MnO_5 (?).

OXIDES, SESQUI: Hematite (Fe_2O_3).

PHOSPHATES, ANHYDROUS: APATITE ($(CaF)Ca_4P_3O_{12}$).

PHOSPHATES, HYDROUS; Vivianite ($Fe_3P_2O_8$).

SULPHATES, ANHYDROUS: Barite ($BaSO_4$), Celestite ($SrSO_4$), Anglesite ($PbSO_4$).

SULPHATES, HYDROUS: Gypsum ($CaSO_4.2H_2O$).

SULPHIDES, DI: Pyrite (FeS_2), Marcasite (FeS_2).

SULPHIDES, MONO: Sphalerite (ZnS), Galena (PbS), Chalcocite (Cu_2S), Cinnabar (HgS).

SILICATES, HYDROUS: Kaolinite ($H_4Al_2Si_2O_4$), Gümbelite ($SiO_2.Al_2O_3.Fe_2O_3.MgO.K_2O.Na_2O.H_2O$), Glauconite (Hydrous silicate of Fe and K), Margarite ($H_2CaCl_4Si_2O_{12}$).

SILICATES, SUB: Calamine ($H_2Zn_2SiO_5$).

SILICON, OXIDES OF: Flint (SiO_2), Silica (Sio_2), Sand (SiO_2).

REFERENCES TABLE II

BERNHARD, *Éléments de Paléontologie*, 1895.

GEIKIE, *Text-Book of Geology*, 3d ed., 1893.

GRATACAP, *American Naturalist*, Vol. XXXI, No 363.

NICHOLSON and LYDEKKER, *Manual of Paleontology*, 3d ed., Vol. I, 1889.

REIS, "Ueber Petrifikation der Muskel," *Archiv für mikroskopische Anatomie*, Vol. XLI.

TRABUCCO, *La Petrificazione*, 1887.

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WHITE, *Bulletin of the United States Geological Survey*, Vol. I, No. I, Art. 8, 1879.

———*Bulletin of the United States Geological and Geographical Survey of the Territories*, Vol. V, 1880.

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CAMBRIAN FOSSILS FROM THE PIOCHE MOUNTAINS, NEVADA

FRED J. PACK

THE FOSSILIFEROUS HORIZONS

The fossils which are used as a basis for this contribution were collected by the writer in the fall of 1905 and the early part of 1906. Mr. Charles D. Walcott visited the district in 1885, and discovered a very fossiliferous horizon which he has correlated with the Middle Cambric. He also gathered a supposed Lower Cambric fauna from a point about six miles east of Pioche. From both these places he obtained several forms that had not been previously described. He has recorded the results of his investigations in *Bulletin No. 30* of the United States Geological Survey. So far as the writer is aware, no other study has been made of this fauna.

Some interesting problems have arisen in the attempt to correlate the Pioche section with the horizons elsewhere. In America the Cambric of the eastern states has received by far the most attention; it has been divided into zones, each of which is represented by a characteristic fauna. The following subdivisions are generally recognized:

Upper Cambric—Dikellocephalus zone
Middle Cambric—Paradoxides zone
Lower Cambric—Olenellus zone

In Nevada the upper and the lower zones are represented by forms which are almost identical with those of similar horizons in the East, but the middle one is characterized by an almost entirely new series. Olenellus and Dikellocephalus are separated in every case by more than 1,000 feet of conformable strata, which carry in places the new forms and some old ones, none of which are elsewhere typically representative of any definite horizon. This condition has made correlation difficult; Walcott, however, has referred these formations to the Middle Cambric. Dr. G. F. Matthew does not concur in this opinion, but thinks that they properly belong to the Upper Cambric.

He further believes that a proper correlation would place the Olenellus fauna above the Paradoxides, and therefore at least as high as upper Mid-Cambric.[1] Throughout western America the Olenellus zone is preceded by thick quartzite beds, which Matthew believes are equivalent to the Protolenus and Paradoxides zones. Chamberlin and Salisbury state that "in the Hudson-Champlain valley the Olenellus fauna appears to have lived on until the advent of the Dikellocephalus fauna."[2] They consider it possible "that the Olenellus of the West and of the Hudson-Champlain valley may have been contemporaneous with the Paradoxides of the East," although they incline to the opinion that it was contemporaneous with the Holmia. At Newton, N. J., Mr. Stuart Weller found a supposed Olenellus species in the undoubted Dikellocephalus zone. In speaking of the value of this specimen, he says:

> It suggests the possibility of a much longer range for the genus Olenellus in geologic time than has been ascribed to it. This genus is usually considered as particularly characteristic of the very lowest Cambrian strata, but here it seems to be associated with the fauna which bears unmistakable marks of the upper Cambrian age.[3]

The exact stratigraphic position of the Olenellus zone is not therefore established. With our present knowledge it is impossible to state whether it is Upper or Lower Cambric, but it appears that Walcott's view is supported by the more evidence. The writer has collected several new forms, but they give no further information as to the position of this series. At present, however, we shall adopt the classification of Mr. Walcott.

In the Pioche Mountains the Lower and Middle Cambric only are represented; the Upper has been removed by erosion. Faulting has so complicated matters that a continuous section cannot be obtained, but one made up from different places is as follows:

5.	Limestone	800 feet
4.	Shale	75 "
3.	Limestone	600 "
2.	Shale	400 "
1.	Quartzite	1500 "

[1] *Transactions of the Royal Society of Canada*, 1899, Second series, Vol. V., pp. 67, 68.

[2] Chamberlin and Salisbury. *Geology*, Vol. II, p. 245.

[3] Geological Survey of New Jersey, *Paleontology*, 1902, Vol. III, p. 13.

The Olenellus fauna is confined to the lower 100 feet of No. 2, a part which is not exposed in the area covered by this report. Walcott gives the following list of fossils which he collected at a point five or six miles east of Pioche:

Eocystites?? longidactylus	Hyolithes billingsi
Lingulella ella	Olenellus gilberti
Kutorgina pannula	Olenoides levis
Acrothele subsidia	Crepicephalus augusta
Acrotreta gemma	Crepicephalus liliana
Orthis highlandensis	

No. 4 of the section given above comprises the second strongly marked faunal horizon. It is best exposed in the Half Moon Gulch about two miles west of Pioche. It forms part of the south member of the anticline, and is nearly horizontal, although occasionally it is slightly tilted. Mining operators have thrown large quantities of this material over their dumps; it was from these places that most of the writer's fossils were collected. The shale also occurs near the city water-tank on the hill southwest of Pioche; the outcrop, however, is highly altered and consequently most of the fossils are destroyed. The following is a list of the species thus far obtained at this horizon:

Eocystites?? longidactylus	Bathyuriscus productus
Lingulella ella	Bathyuriscus howelli
Kutorgina pannula	Lingulella genei
Hyolithes billingsi	Ptychoparia kempi
Ptychoparia piochensis	Zacanthoides grabaui
Zacanthoides typicalis	

DESCRIPTION OF SPECIES

ECHINODERMATA

GENUS **EOCYSTITES,** Billings

EOCYSTITES, Billings, 1868: *Acadian Geology*, p. 643, Fig. 220.

Eocystites?? longidactylus, Walcott

(Plate I, Figs. 1, 1*a*, 1*b*)

Eocystites?? longidactylus, Walcott, 1886: *Bulletin No. 30*, U. S. Geological Survey, p. 94, Plates 5, 6.

In 1886 Mr. Walcott tentatively referred the species *longidactylus* to the genus Eocystites, awaiting a further description of *Eocystis*, Billings, (1868), and *Protocystis*, Hicks (1872). These forms, however, have never been properly described or figured, and, according to Bather, "since they cannot be well distinguished from *Eocystites* (*?*)

longidactylus, that species must be taken as an example of the genus." The most important features are: "the presence around the mouth of not less than ten biserial brachioles with long covering-plates ('short pinnulæ' of Walcott); the varying development of radiating stereom-folds on some of the plates;" the disposition of the plates "without apparent order, and varying in form, size, and surface characters on the same body." The specimens collected by Walcott are well preserved in some parts and badly crushed in others. Those in the writer's collection are in some respects very good; they do not, however, show all the features noted by Walcott, but in addition they possess some very interesting points not before revealed. Among these are a very primitive form of stem, and highly lobate plates.

The writer's collection of these species consists of several arms (all of which show the covering-plates), some loose plates, and a very beautiful specimen showing the lower part of the calyx with the stem attached. The plates are considerably misplaced, and the proximal part of the stem is somewhat crushed; otherwise the specimen is in a very good state of preservation. The drawing in Plate I is that of a cast.

None of the arms, with but one exception, shows the biserial nature of the brachioles; this may be due to the position from which they are viewed. Walcott observed one "pinnule" to each arm plate, but the writer's best-preserved specimen shows two to each plate (Fig. 1*a*).

As noted above, the plates are described as "numerous, disposed without apparent order, and varying in form, size, and surface characters;" and further, "the margin of many of the plates appears to be so indented as to have an opening or pore that passed into the central cavity." The plates in the writer's specimen are also numerous, of varying size, and are irregularly placed, but the surface characters described by Walcott are entirely absent. The plates are all smooth and slightly concave. The marginal indentions are carried so far that the plates are completely lobed (Fig. 1*b*). At first sight the lobes of the various plates appear to interlock, and thus form a rather rigid connection; but a closer examination has convinced the writer that this apparent interlocking is due to the intrusion of foreign material. Some few plates, however, appear to show this condition. It is probable that the plates were so arranged that only the

extreme ends of the lobes touched. They vary in size and form; in general outline many of them are decidedly hexagonal, others are pentagonal, and still others are nearly circular. The ones nearest the stem do not show the presence of lobes. The lobate plates closely resemble those of the embryonic Antedon.

The stem is composed of numerous sac-like plates, varying in size and irregularly placed (Fig. 1). The diameters of about eight of these appear to equal the circumference of the stem. The stem tapers slightly from the calyx down, and near the lower end turns gently to one side. It is probable that the stem was flexible throughout and possibly prehensile in the lower portion. The extreme tip is not revealed.

The greatest value of this fossil lies in the stem or pedicle. It is known that some of the primitive cystoids, as *Aristocystis* (Barrande, 1887), possess no stem whatever. Others, as *Dendrocystis* (Barrande, 1887), have a rudimentary stem, the plates of which are irregular near the calyx, but pass into comparatively large solid plates farther down. In such forms as *Trochocystis* (Barrande, 1859–87; syn. *Trigonocystis*, Haeckel) the stem is short and tapering and composed of regularly arranged plates. In the species under discussion the plates composing the calyx, as well as the stem, appear to have been arranged with no regularity whatever. *Eocystites?? longidactylus*, therefore, appears to be the earliest form of stemmed cystoid yet described.

Location and formation: Two miles west of Pioche at the Abe Lincoln Mine, on the southwest slope of the mountains, in a pinkish shale of Mid-Cambric age.

PTEROPODA

GENUS **HYOLITHES**, Eichwald

HYOLITHES, Eichwald, 1840: *Sil. schicht. Syst. in Ehstl., p. 97.*

Hyolithes billingsi, Walcott

Salterella obtusa, Billings, 1861: *Geology of Vermont*, Vol. II, p. 955.

Hyolithes primoirdialis? White, 1874: *Geographical and Geological Exploration and Survey, West of the 100th Meridian*, Preliminary Report, Invertebrate Fossils, p. 6.

Hyolithes billingsi, Wallcott, 1886: *Bulletin No.* 30, U. S. Geological Survey, p. 134, Plate 13.

This form was not collected by the writer, although Walcott has described it from this locality.

BRACHIOPODA

GENUS **LINGULELLA**, Salter

LINGULELLA, Salter, 1861: *Memoir, Geological Survey of Great Britain*, p. 333.

Lingulella ella, H. & W.

(Plate 1, Figs. 2, 2*a*)

Linguelepsis ella, Hall and Whitefield, 1877: *Geological Exploration of the Fortieth Parallel*, Vol. IV, p. 232, Plate 1.

Lingulella ella, Walcott, 1886: *Bulletin No. 30*, U. S. Geological Survey, p. 97, Plates 7, 8.

Walcott has recently described this form under the name *Obolus (Westonia) ella*. It is found in great abundance wherever the shale member is available, and is probably the best-preserved of any of the fossils.

Location: Himon Mine, Chisholm Mine, Half Moon Mine, and Abe Lincoln Mine.

Lingulella genei, n. sp.

(Plate I, Figs. 3, 3*a*, 3*b*)

Small shell, rarely exceeding 2^{mm} in length, elongate ovate or semielliptical; about one-fifth longer than broad; widest portion a little nearer the front which is broadly rounded. Dorsal valve generally ovate and rounded at the beak. Both valves moderately convex.

The interior cast of the dorsal valve is well marked by three scars, the middle one of which extends more than half-way toward the front, the outer ones not quite so far.

In general this species resembles *Lingulella granvillensis*, found at Whitehall, N. Y. It differs in the ovate form, in the surface markings, and in the muscular scars.

This fossil occurs abundantly in the shales at the Half Moon Gulch. It is associated with *Zacanthoides typicalis*, *Ptychoparia poichensis*, and *Eocystites? ? longidactylus*. In fact, the writer has one slab carrying these four fossils. It is preserved in beds of pink and brown calcareous shale; the fossil is of the same color as the inclosing rock, but a little darker.

Location: Abe Lincoln Mine.

GENUS **KUTORGINA**, Billings

KUTORGINA, Billings, 1861: Pamphlet and *Geology of Vermont*, Vol. II, p. 948.

KUTORGINA, Davidson, 1871: *Manual of British Fossil Brachiopods*, Vol. III, p. 342.

Kutorgina pannula, White.

(Plate II, Figs. 1, 1*a*, 1*b*, 1*c*)

Trematis? pannula, White, 1874: *Geographical and Geological Exploration and Survey West of the 100th Meridian*, Preliminary Report "Invertebrate Fossils," p. 6.

Kutorgina pannula, Walcott, 1886: *Bulletin No. 30*, U. S. Geological Survey, p. 105, Plates 7, 8.

The writer's collection contains but one specimen of this species, and it differs slightly from all of the forms thus far figured. In the genus *Kutorgina* the hinge line extends nearly the whole width of the shell. The outline of *K. pannula* is "apparently subcircular or a little broader than long; apex moderately pronounced and situated near the posterior margin." This condition, as well as the characteristic surface markings, are well shown in the specimen at hand. It differs chiefly from the ones described and figured in being larger and in having almost square shoulders. The writer has produced in outline Walcott's figures, which, with the one of the writer's, form a complete series, ranging from the type with very sloping shoulders to the one with square shoulders. This feature is accompanied with an increase in size.

Location: Abe Lincoln Mine.

CRUSTACEA

TRILOBITA

GENUS **BATHYURISCUS**, Meek

BATHYURISCUS, Meek, 1873: *Sixth Annual Report*, U. S. Geographical Survey of the Territories, p. 484.

Bathyuriscus howelli, Walcott

(Plate II, Figs. 2, 2*a*)

Bathyuriscus howelli, Walcott, 1886: *Bulletin No. 30*, U. S. Geological Survey, p. 216, Plate 30.

Emblominus rotunda, Roem., 1887: *Proceedings of the Academy of Natural Sciences*, Philadelphia, 1887, p. 16, Pl. I.

The entire head of the creature has not been found. The pygidia, which occur in abundance, show considerable variation in form and

size. Walcott originally figured the head with three pairs of glabellar furrows, but it was later shown that four were present. The writer found two heads somewhat resembling the type. They differ from it mostly in the presence of a frontal margin, which is well developed in the antero-lateral portion. There are four pairs of well-defined glabellar furrows; the posterior pair points obliquely backward; the second pair points almost directly across; the third and fourth pairs point obliquely forward. The glabella is broadly expanded in front of the eyes. The postero-lateral limbs are not preserved. The two heads were collected at the Half Moon Mine. The writer tentatively refers them to this species.

Location: Himon Mine, Abe Lincoln Mine, Half Moon Mine.

Bathyuriscus productus, H. & W.

(Plate II, Figs. 3. 3*a*, 3*b*)

Ogygia producta, Hall & Whitefield, 1887: *Geological Exploration of the Fortieth Parallel*, Vol. IV, p. 244, Plate 2.

Bathyuriscus producta, Walcott, 1886: *Bulletin No. 30*, U. S. Geological Survey, p. 217, Plate 30.

This species occurs in great abundance; its remains are largely fragmentary, the pygidia being the most common.

Location: Himon Mine and Abe Lincoln Mine.

GENUS **PTYCHORPARIA**, Corda

PTYCHOPARIA, Corda, 1847: *Prodram. Mon. böhm. Trilobiten*, p. 141.
Equals *Conocephalus*, Zenker, 1833.
Equals *Conocephalus*, Barrande, 1852.

Ptychorparia piochensis, Walcott

(Plate II, Figs. 4, 4*a*, 4*b*, 4*c*)

Ptychoparia piochensis, Walcott, 1886: *Bulletin No 30*, U. S. Geological Survey, p. 201, Plate 28.

This is a very characteristic form; it occurs throughout the entire shaly stratum, and usually is abundantly represented. The heads are most commonly preserved, but almost perfect fossils are frequently found. In all of the specimens figured by Mr. Walcott the frontal rim appears to bend downward. This is probably a fault of the drawing, as not a single form in the writer's collection shows this condition. The frontal margin turns somewhat abruptly *upward* into the frontal rim (Fig. 4*a*).

Location: Himon Mine, Chisholm Mine, Abe Lincoln Mine, Half Moon Mine, and at the upper water tank near Pioche.

Ptychoparia Kempi, n. sp.

(Plate III, Fig. 1.)

This form is known only by the head inside of the free cheeks.

General outline of the head moderately quadrate; width, exclusive of postero-lateral limbs, about equal to height. Glabella short, conical, with straight lateral sides converging from base forward to gently rounded front; slightly longer than one-half height of head; one and one-half times longer than posterior width; marked by three pairs of glabellar furrows, pointing directly across and nearly uniting at center; moderately well-marked occipital groove, which deepens into pit near lateral margin of glabella; occipital ring slightly convex, and provided with well defined knob, or perhaps spine.

Frontal limb broad, and concave toward front, where it turns slightly upward, forming a narrow frontal rim; half as high as wide; marked with fine stria radiating from front of glabella and extending about half-way to anterior rim; antero-lateral portion broadly rounded.

Fixed cheeks separated from glabella by deep dorsal furrows; elevated inside eye-lobe, and forming a cone or rounded pyramid the apex of which is nearly twice as high as glabella; anterior slope more gentle than posterior, which pitches abruptly down into postero-lateral groove; fixed cheeks moderately broad, slightly contracted just in front of eye, and then expanded into broad anterior limb.

Eyes narrow, reaching from front of glabella to opposite elevation on fixed cheek.

Postero-lateral limbs elongate, narrow, curving gently backward, and traversed part way out by groove.

The species *P. subcoronata* is a closely allied form, but *P. kempi* may be readily distinguished from it by the absence of the peculiar boss in front of the glabella, and by the presence of the elevations on the fixed cheeks.

The one specimen by which this form is known preserves only the glabella, frontal margin, free cheeks, and postero-lateral limbs. It is fairly well preserved, and is contained in a brown shale tinted with green.

Location: Half Moon Mine.

GENUS ZACANTHOIDES, Walcott

Zacanthoides, Walcott, 1888: *American Journal of Science*, Third Series, Vol XXXVI, p. 165.

Zacanthoides typicalis, Walcott

(Plate III, Figs, 2, 2*a*, 2*b*, 2*c*, 2*d*, 2*e*, 2*f*)

Olenoides typicalis, Walcott, 1886: *Bulletin No. 30*, U. S. Geological Survey, p. 183, Plate 25.

Zacanthoides typicalis, Walcott, 1888: *American Journal of Science*, Third Series, Vol. XXXVI, p 165.

This is the most widely distributed and characteristic fossil of the Mid-Cambric horizon at Pioche. Several almost perfect specimens were collected. The heads, free cheeks, and fragments of the body are extremely abundant. The material at hand, however, differs in a number of details from the type specimen as figured, but these differences are not all constant, as there is considerable variation in the collection. The writer has found no specimen that shows the exact arrangement of the pleural lobes, as indicated in the figure of the type. It will be seen by reference to this figure[1] that from posterior to anterior each lobe overlaps the succeeding one. This is probably a fault of the drawing, as all the specimens at hand show the opposite condition.

Of the entire collection of no less than twenty-five free cheeks and the attached genal spines there is not one specimen comparable to those in the figure to which reference has just been made. The most common spine is much straighter, and makes a larger angle with the axial lobe (Fig. 2). Several others, somewhat resembling those of the type, show a decided outward flexure in the backward extension (Fig. 2*e*). There are three or four nearly perfect specimens, in which the genal spines pass back as far as the extremity of the pygidium. In this form the spines on the postero-lateral limbs are also unusually long (Figs. 2*b*, 2*c*). Another very spinose specimen shows the presence of a long spine on the next to the last pleural segment (Fig. 2*d*). These conditions are rather confusing, as otherwise the specimens are all alike. The differences, however, can hardly be considered sufficient to justify the making of a new species. It may be that these variations in spinosity are simply sexual peculiarities, as suggested by Barrande in the case of *Paradoxides harlani*.

Location: Half Moon Mine, Chisholm Mine, Abe Lincoln Mine, and at the upper water-tank above Pioche.

[1] *Bulletin No. 30*, U. S. Geological Survey, Plate 25, Fig. 2.

Zacanthoides grabaui, n. sp.

(Plate III. Figs. 3, 3*a*, 3*b*)

This species is known only by the head, free cheeks, and some fragments of the thoracic segments with spines attached. Two of the specimens (Fig. 3 b) were collected by Mr. Charles Of.

General form of the head triangular; glabella elongate, a little more than twice as long as broad; sides parallel; front broadly rounded; surface moderately convex; slight ridge extending lengthwise at summit; three pairs of well-marked glabellar furrows, the posterior pair pointing obliquely backward, the second pair directly across, and the anterior pair slightly forward; occipital furrow fairly well marked, and occipital ring provided with a knob or spine; postero-lateral limb provided with short thick spine.

Frontal margin expanded into broad triangular area, one of the apices pointing directly forward; rim on either side of anterior apex slightly concave backward; triangular area, provided with well-pronounced frontal rim; area flat with slight elevation near center; marked with stria radiating from front of glabella; frontal rim marked with fine stria extending longitudinally.

Fixed cheeks moderately broad inside on the eye-lobe, highly contracted just beyond front of eye, and then expanded into triangular frontal margin.

Free cheeks broad and flat, bordered anteriorly and laterally by heavy rim extending backward into a slightly curved genal spine, which apparently does not pass beyond the fifth thoracic segment.

Eyes narrow and long, reaching from opposite anterior pair of glabellar furrows to opposite occipital ring.

Axial lobe apparently same width as glabella, and rather highly convex; first pleural lobe extends through an abrupt angle into a short stout spine; in the second the spine is longer and the angle less abrupt; in the third the angle disappears, the lobe and spine forming a gentle curve.

In some ways this form resembles *Z. typicalis*, but differs from it in the general shape of the head, the frontal margin, and the genal spines.

Location: Half Moon Mine.

PLATE I

FIG. 1.—*Eocystites?? longidactylus*, Walcott.

1. View of specimen showing the sac-like stem and the lobed plates; twice natural size. Collection Columbia University Museum, No. 20001.

1*a*. An arm showing the arrangement of the covering-plates; twice natural size. Collection Columbia University Museum, No. 20002.

1*b*. Slightly concave plate showing the lobate arrangement at margin; four times natural size. Collection Columbia University Museum, No. 20003.

FIG. 2.—*Lingulella ella*, H. & W.

2. View of a well-preserved specimen; twice natural size. Collection Columbia University Museum, No. 20004.

2*a*. Elongate specimen; twice natural size. Collection Columbia University Museum, No. 20005.

FIG. 3.—*Lingulella genei*, n. sp.

3. View of dorsal valve showing distribution of the concentric lines; seven times natural size. Prototype. Collection Columbia University Museum, No. 20006.

3*a*. Ventral valve; seven times natural size. Paratype. Collection Columbia University Museum, No. 20006.

3*b*. Internal mold of dorsal valve; seven times natural size. Paratype. Collection Columbia University Museum, No. 20002.

PLATE II

FIG. 1.—*Kutorgina pannula*, White.

1. View of a large square-shouldered specimen; twice natural size. Collection Columbia University Museum, No. 20009.

1*a*. Outline drawing of type specimen as figured in *Bulletin No. 30*, U. S. Geological Survey.

1*b*, 1*c*. Outline drawings of specimens as figured in *Bulletin No. 30*, U. S. Geological Survey.

FIG. 2.—*Bathyuriscus howelli*. Walcott.

2. Specimen showing the four pairs of pleural grooves extending nearly to the margin; natural size. Collection Columbia University Museum, No. 20011.

2*a*. Specimen tentatively referred to this species; it shows four pairs of glabellar furrows, also well-developed antero-lateral frontal margin; twice natural size. Collection Columbia University Museum, No. 20012.

FIG. 3.—*Bathyuriscus productus*, H. & W.

3. View of well-preserved head, natural size. Collection Columbia University Museum, No. 20014.

3*a*. View of pygidium showing well-defined, broad, flattened border; no rings on axis; natural size. Collection Columbia University Museum, No. 20015.

3*b*. View of pygidium showing rings on axis; border not so flat as in 3*a*; natural size. Collection Columbia University Museum, No. 20016.

FIG. 4.—*Ptychoparia piochensis*, Walcott.

4. View of typical specimen; twice natural size. Collection Columbia University Museum, No. 20018.

4*a*. View of typical head showing the elevated frontal rim; twice natural size. Collection Columbia University Museum, No. 20019.

4*b*. View of free cheek; natural size. Collection Columbia University Museum, No. 20020.

4*c*. View of what appears to be an hypostoma with doublure attached; twice natural size. Collection Columbia University Museum, No. 20021.

PLATE III

FIG. 1.—*Ptychoparia kempi*, n. sp.

1. View of prototype showing character of frontal margin and elevations inside eye-lobe; natural size. Collection Columbia University Museum, No. 20023.

FIG. 2.—*Zacanthoides typicalis*, Walcott.

2. View of specimen closely resembling the type; twice natural size. Collection Columbia University Museum, No. 20024.

2*a*. View of head showing the postero-lateral limbs attached; twice natural size. Collection Columbia University Museum, No. 20025.

2*b*. Specimen showing remarkably long genal spines, long spines on postero-lateral limbs, but, so far as revealed, no spines on thoracic segments; twice natural size. Collection Columbia University Museum, No. 20026.

2*c*. Specimen showing considerable spinosity, twice natural size. Collection Columbia University Museum, No. 20027.

2*d*. Specimen with long genal spines, also long spine on the next to the last thoracic segment; natural size. Collection Columbia University Museum, No. 20028.

2*e*. Very commonly associated free cheek showing outward flexure toward the end of spine; twice natural size. Collection Columbia University Museum No. 20003.

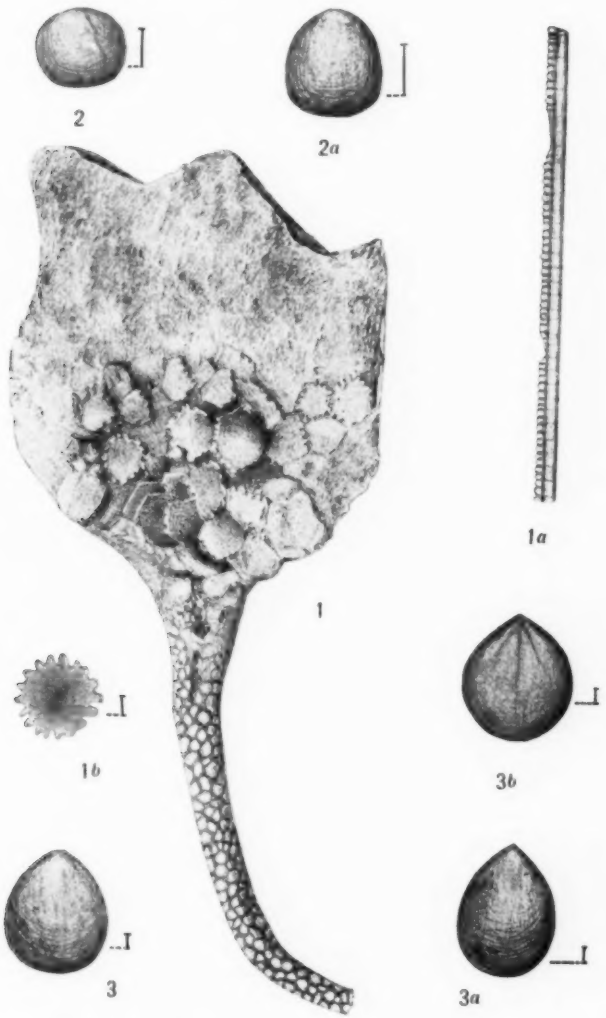
2*f*. Hypostoma associated with this species; natural size. Collection Columbia University Museum, No. 20029.

FIG. 3.—*Zacanthoides grabaui*, n. sp.

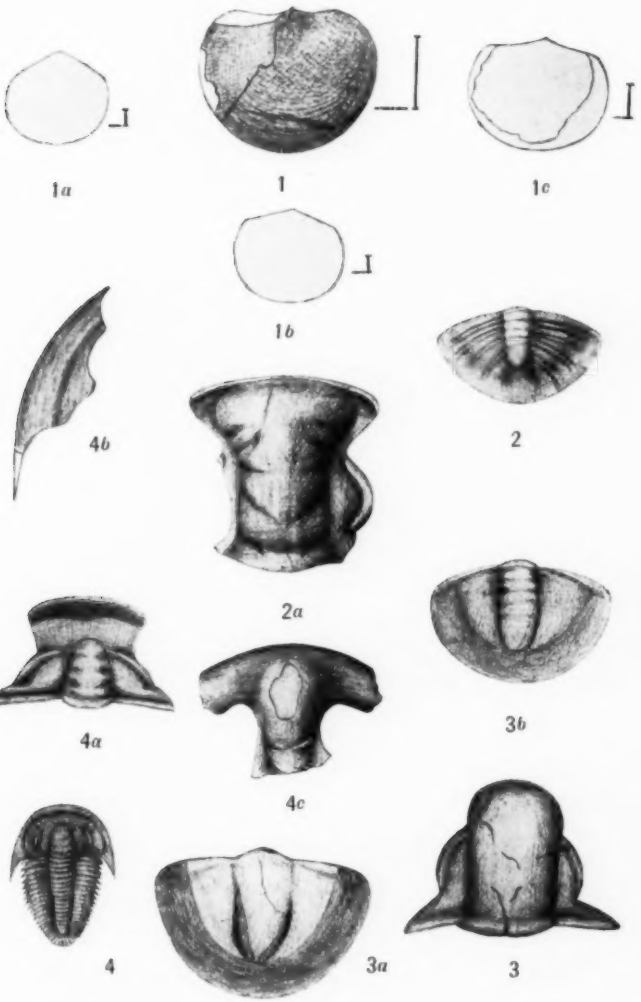
3. Prototype showing the general form of head, triangular frontal margin, and nearly straight genal spines; natural size. The free cheek has been slightly adjusted. Collection Columbia University Museum, No. 20031.

3*a*. Paratype showing the general nature of the head, also the knob or spine on the occipital ring; natural size. Collection Columbia University Museum, No. 20031.

3*b*. Cast of paratype showing nature of third pleural lobe and the attached spine, natural size. Collection Columbia University Museum, No. 20032.



F. J. Pack and R. B. Johnson, Del.



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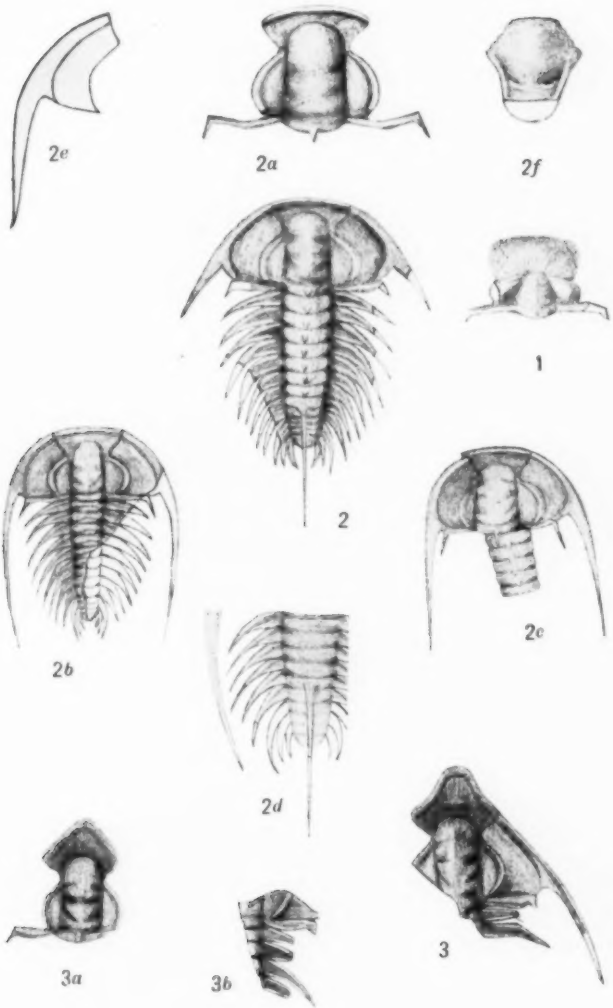


F. J. Pack, Del.

SOME LOCAL EFFECTS OF THE SAN FRANCISCO EARTHQUAKE

STEPHEN TABER
Leland Stanford Junior University

The principal damage done by the San Francisco earthquake of April 18, 1906, was confined to a long, narrow area extending along the Pacific coast in a northwest-and-southeast direction, with the city of San Francisco near its center. The area in which the greatest damage was done is a little over 200 miles in length and scarcely 40 miles in width. The earthquake may be accounted for by the geological structure. The principal valleys of California have been formed by a system of parallel faults running in a general northwest-and-southeast direction, and the disturbance occurred along one of these old fault-lines.

The particular fault which caused the earthquake is the Stevens Creek fault; it has been traced across the Santa Cruz quadrangle by Dr. J. C. Branner and Dr. J. F. Newsom, and is described by them in the unpublished Santa Cruz folio of the United States Geological Survey. It runs from Crystal Springs Lake through Woodside and the Portola Valley, over the saddle that joins Black Mountain with the crest of the Santa Cruz Range, down the Stevens Creek canyon, crosses Campbell Creek about 2 miles southwest of Saratoga and continues in the same southeasterly direction toward Loma Prieta. From Crystal Springs Lake the fault has been traced toward the northwest by Professor A. C. Lawson through San Andreas Lake and out into the ocean near Mussel Rock, about 7 miles south of the Cliff House at San Francisco.

The topography appears to indicate that the fault-line continues its northwesterly course through Bolinas Bay and Tomales Bay, and that it finally leaves the coast near Point Arena in Mendocino County.

The present paper deals only with the movements that took place along this fault-line between Crystal Springs Lake and Black Moun-

tain, and with the effects of the earthquake on the district lying on both sides of the fault-line and extending from San Francisco Bay to the Pacific Ocean.

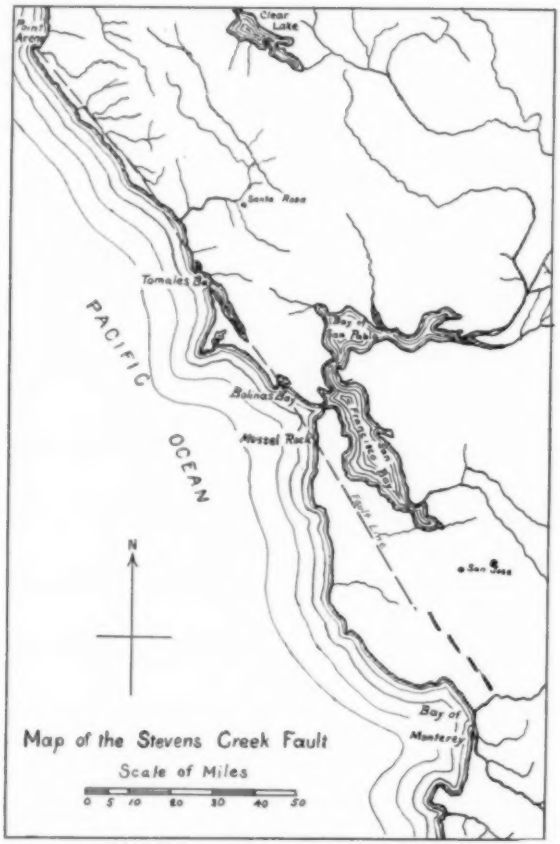


FIG 1.

The Stevens Creek fault is one of the most recent, for it cuts gravel beds that were laid down as late as the Pliocene or perhaps Pleistocene period. The old uplift along the Stevens Creek fault is on the northeast side, and the rocks on both sides of the fault dip

in a northeasterly direction. The Miocene sandstones that form the greater part of the Santa Cruz Range come down to the fault-line on the west, but on the east side erosion has removed the overlying beds and exposed the Franciscan series, so that it is only at some distance away from the fault toward the east that the Miocene sandstones and gravels reappear.

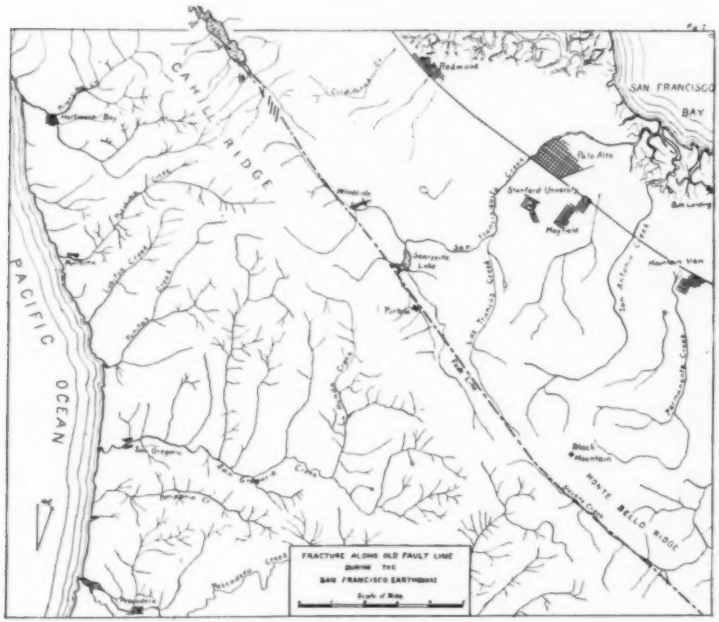


FIG. 2.

At about fifteen minutes after five o'clock on the morning of April 18, 1906, the Stevens Creek fault was suddenly refractured, and a new displacement occurred along the old fault-line, producing the earthquake that shook the adjacent region.

This new displacement is chiefly lateral, the southwest side of the fault having moved toward the northwest, or *vice versa;* and in some places this has been accompanied by a small uplift on the northeast, or a small downthrow on the southwest, or both. The

lateral displacement is well defined, as far as it has been traced, and at some points amounts to as much as 9 feet. The vertical displacement in most places is not so evident, but about a mile southeast of Portola there is an uplift of 2 feet on the northeast side, and the same amount of vertical displacement has been observed on Black Mountain.

The valleys through which the old Stevens Creek fault runs are filled with silt and gravels, so that it is impossible to get at bed-rock

FIG. 3.—Road crossing the fault-line two miles southeast of Portola. There is a vertical uplift on the northeast side of the fracture at this place.

along the fault-line, but it is probable that the rocks along this line have been so broken and crushed by past movements that they would offer little or no additional information in regard to the recent displacement.

Through the Portola Valley, and for about 3 miles northwest of Woodside, the fracture runs in a continuous and almost straight line. At a little distance it looks as though a furrow had been run down the valley with a big plow. In places the earth has been

piled up into ridges 2 or 3 feet high, and at other places fissures have been opened that measure 2½ feet in width. Two and a half miles southeast of Portola the fissure is 3 feet across. The ground is usually cracked and broken for a distance of 10 or 15 feet on both sides of the main fracture, which in places splits up into numerous minor cracks.

Two miles southeast of Crystal Springs Lake the resistance to

FIG. 4.—Showing a fence that crossed the fault at an oblique angle. The post shown in the photograph was split and pulled apart and the wires broken.

displacement appears to have been greater, and, instead of slipping along a straight line, the ground has been broken into a belt of parallel, north-and-south, shearing cracks, running at an angle of approximately 45° with the general movement. Some of these shearing cracks are from 1½ to 2 feet wide, and the belt of cracks extends for a quarter of a mile or more.

Black Mountain was badly shattered, and there are numerous

cracks running over it in all directions. Fences crossing the fracture are broken; those that run in a north-and-south direction have their boards bent into arches or crushed, and the ends shoved past each other, while those that cross in a northwest-and-southeast direction have been pulled apart, and wire fences have been broken by tension. Fences that cross the fracture at right angles have been broken and displaced 8 or 9 feet.

The photograph (Fig. 6) shows a line fence crossing the fault

FIG. 5.—Showing a fence that was broken and offset eight feet where it crossed the fracture.

a mile southeast of Woodside. This fence was broken and displaced over 8 feet, but had been repaired before the photograph was taken. The man at the right in the picture is holding an 8-foot transit rod, and he is standing in line with the continuation of the fence on the far side of the fracture. The crack crosses the fence just back of where he is standing.

A striking evidence of displacement is shown in the earth dam that divides the Crystal Springs Lake. This dam is about 500 feet

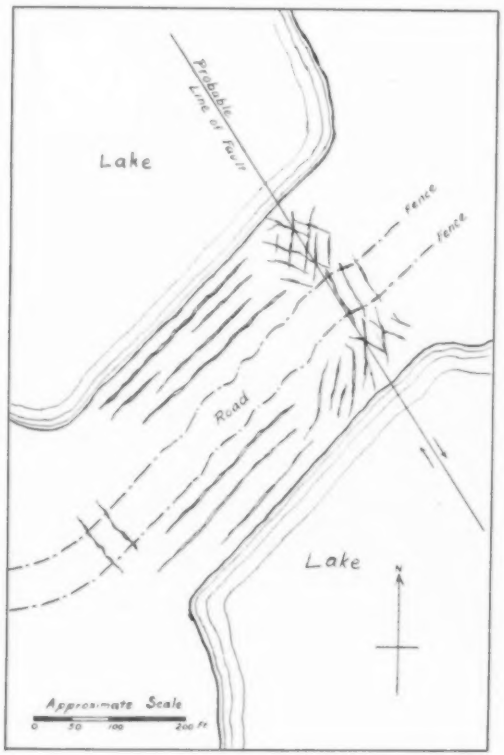
in length, and the road from San Mateo to Half Moon Bay runs along its crest. The accompanying sketch (Fig. 7) shows the position and direction of the cracks that were formed in the dam. The larger cracks are about 6 inches wide and are parallel with the dam. Smaller intersecting cracks were formed near the northeast end of the dam along the probable line of the fault, and the road was offset about 6 feet at this point. The fences on both sides of the

FIG. 6.—Photograph of a fence crossing the fault-line at right angles. The man is holding an eight-foot transit rod and stands in line with continuation of the fence on the far side of the fracture. The fence was repaired before the photograph was taken.

road were broken in a number of places, and the unbroken boards were bent and arched so as to give a serpentine appearance to the fences. The wires of a telephone line crossing the dam sag in great loops.

It seems probable that the total displacement is greater than the amount that may be directly measured at any place along the line of the fracture, for there is evidence of drag in the soil for a consid-

erable distance on both sides. Water-pipes at a distance of several hundred feet from the fault-line have been pulled apart, telescoped, or bent in the direction of the movement, and fences formerly straight



Dam at Crystal Springs Lake
showing cracks formed by the displacement

FIG. 7.

have been bent into a slight curve for a distance of 200 or 300 yards from the fracture.

The intensity of the shock was greatest along the line of faulting, and decreases as one goes away from this line. In comparing the

intensity of the shock at different places, the best evidence was supplied by the oak trees broken and uprooted where the intensity was greatest, by the percentage of country water-tanks thrown down, and, as the intensity decreased, by the condition of plastering in houses and the number of brick chimneys found standing.

There are many white oaks (*Quercus lobata*) growing in the valleys through this section of the country, and in a belt extending

FIG. 8.—An oak tree six feet in diameter uprooted by the earthquake three hundred yards from the fault line.

for not more than 400 or 500 yards on each side of the fracture many of these trees have been uprooted or have had large branches whipped off. Sound limbs 2 feet thick were broken off by the shock, and there are trees having a diameter of more than 6 feet that were overturned during the earthquake. About 300 yards southwest of Searsville Lake a live oak (*Quercus agrifolia*), growing within a few feet of the fracture, was split down the trunk by the violence of the movement, but is still standing.

On Cahill Ridge, 2 miles southwest of the fault-line, there are

redwoods (*Sequoia sempervirens*) that had their tops snapped off 75 or 100 feet above the ground. The intensity of the shock was much less at this point than near the line of fracture, but the redwood is brittle compared with the oak.

Frame houses, strongly built and having good foundations, stood the shock well, even when close to the fault-line, but brick and stone structures were badly damaged at distances of more than 12 miles from the fracture. Fortunately for the inhabitants, most of the houses near the fault-line were one-story frame buildings.

Most of the water-tanks that stood within 3 or 4 miles of the fracture were thrown down, but farther away the percentage of tanks that are standing gradually increases. With but few exceptions, all brick chimneys within 3 or 4 miles of the fault-line were thrown down, but at a distance of 8 or 9 miles probably more than 50 per cent. are still standing.

Within the area under discussion the earthquake seems to have consisted of two separate and distinct kinds of movement: one a violent vibration in a northwest-and-southeast direction, parallel to the fracture, and probably caused by the sudden displacement; the other a wave-motion, traveling at right angles to the fracture and generated by the rocks slipping past each other along the fault-line.

It was the first motion that snapped off branches, overturned oak trees and wrecked buildings in the immediate vicinity of the fault-line; and although this motion extended for a considerable distance, the damage it caused was limited to a belt not over a mile distant from the fracture.

The following facts appear to bear out the theory of a violent initial movement parallel to the fault-line. Most of the trees that were overturned fell toward the northwest or southeast, and the buildings that were destroyed near the line of fracture tended to move in the same direction; but frame buildings do not furnish very reliable data. Beds and furniture rolled back and forth in directions parallel to the vibration. The strongest evidence is furnished by the movement of liquids, such as milk and water. In the immediate vicinity of the fracture many places were found where the water had splashed out of reservoirs and tanks on the northwest and southeast sides, and at one place the motion had been so violent

that the water in a large wooden tank had splashed against a roof placed over it with sufficient force to drive shingles from the northwest side. In some places large water-tanks holding 3,000 or 4,000 gallons were almost emptied by the splashing.

The wave-motion was responsible for most of the damage done outside of the narrow belt along the line of fracture. Several people, who were out of doors at the time of the earthquake and several miles from the fault-line, state that the ground appeared to move like the waves of the sea. While these statements cannot be used as conclusive evidence, there are many facts that indicate a true wave-motion, having distinct crests. Water in reservoirs and tanks, standing at a distance of several miles from the fault-line, splashed out on the northeast and southwest sides. At King's Mountain House, a little over 2 miles southwest of the fracture, there were a number of milk-pans setting on shelves. All of the cream went out on the southwest side of the pans, and afterward the milk splashed back and forth, spilling out on both the southwest and northeast sides. At a barn 3 miles northeast of Woodside, heavy carriages standing with their wheels parallel to the fault-line were moved sideways a distance of 6 inches, but did not roll forward on their wheels.

At Stanford University, 4½ miles northeast of the fault-line, the sandstone buildings afford evidence of the wave-motion. Walls running northwest and southeast, when free to fall, fell by toppling over, and the stones lie on the ground in nearly the same relative positions that they occupied while standing. Walls running more nearly parallel to the direction of wave-motion were crushed, and the stones fell in irregular piles, while the walls that are still standing show 45° shearing cracks. Perhaps the best evidence of a true wave-motion is to be found in the arches. When the crest of a wave struck an arch running northeast and southwest, the arch was pulled apart, allowing the keystones to drop a short distance. There are forty-six arches running approximately northeast and southwest in which the keystones dropped, while only twelve arches running northwest and southeast had their keystones lowered, and some of the latter may be accounted for by the falling of neighboring walls. It might be well to state that there were more arches running northwest and southeast than at right angles to that direc-

tion. Most of the keystones dropped only 5 or 6 inches, but some fell out completely.

There are several strongly built, low, one-story frame houses, of the bungalow type, standing within a few hundred feet of the fault, which scarcely had their plaster cracked, excepting where chimneys fell through. Broken oak trees growing close to these houses indicate the intensity of the shock. This suggests that the

FIG. 9.—Photograph of arches at Stanford University, showing keystones lowered during the earthquake. These arches were nearly at right angles to the fault-line.

wave-motion, with its shearing action, was more damaging to walls than a back-and-forth vibration. Another interesting fact in this connection is that most two-story frame buildings at a distance of 5 or 6 miles from the fault-line did not have the plaster cracked on the second floor, although the plaster on the first floor was usually badly cracked and broken.

Brick buildings at a distance of 10 miles from the fault-line showed the effects of a wave-motion. At Guth Landing, on San

Francisco Bay, 9½ miles northeast of the fracture, there was a large brick warehouse, with its ends parallel to the fault-line. The upper half of each end toppled over, but the side walls, although badly cracked, were left standing.

The effects of this wave-motion have not been traced more than 12 miles from the fault-line, but it probably continued with diminished intensity to a considerable distance. In other districts, having a different geological structure, the distances to which these movements could be traced would undoubtedly vary greatly. The wave-motion appears to have been more intense in the soft alluvial deposits of the valleys than in the consolidated beds that form the high ground, but there are not enough houses in the mountains of this district to furnish conclusive evidence on this point.

At Half Moon Bay the intensity of the earthquake was about the same as at Stanford University; but as one goes down the coast, and therefore away from the fault-line, the intensity decreases. At Pescadero, which is about 12 miles from the fault-line, there was scarcely any damage done, but there were no brick or stone buildings in that village.

In regard to the geological effects of the earthquake, there are a few facts of general interest that might be mentioned. Most of the landslides that occurred at this time were on the west side of the Santa Cruz Range. This is probably to be attributed to the greater rainfall on that side of the watershed. The springs and streams on both sides of the range increased in volume after the earthquake, and some creeks on the west side were nearly doubled. All of the streams were muddy for several days after the earthquake.

A marked effect was produced on the artesian belt near the head of San Francisco Bay. Wells that had previously been dry began flowing, and wells that flowed before the shock greatly increased in volume and pressure. The following is one illustration out of many that were recorded: A well near Alviso, at the head of the bay, formerly required a wind-mill to pump the water. At the time of the earthquake the casing was driven 2 feet out of the ground, wrecking the pump, and since that time the well has been flowing under a heavy pressure. In some of the lowlands small cracks were formed, out of which water issued, bringing up mud and sand.

STUDIES FOR STUDENTS

RELATIVE GEOLOGICAL IMPORTANCE OF CONTINENTAL, LITTORAL, AND MARINE SEDIMENTATION[1]

JOSEPH BARRELL

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ADVANCE SUMMARY

The purpose of the following articles is to give a proportionate view as to the relative geological importance of continental, littoral, and marine deposits, and to discuss the use of some criteria for separating them. This is in accordance with the movement which is now taking place from the preliminary qualitative state of geological science to a more balanced quantitative state. To this end, use has been made of the facts of observation concerning present

[1] The contents of the three parts are outlined here. Parts II and III will appear in later numbers.

sedimentation already recorded in the geological literature of the past fifty years, rather than to new observations; and it is thought that a certain value will be attained by bringing together this widely scattered body of information. The references are frequently given to the most accessible source, rather than necessarily to the original statement of facts, frequently difficult of access and sometimes in foreign languages; but the effort has been, not to found arguments upon commonly quoted generalizations, but to go back to their sources, often largely lost sight of, and to examine from this starting-point the quantitative value of those generalizations. The ultimate conclusions will be found to be sometimes in accordance with, sometimes at variance with, views which have frequently been expressed in geological literature. The outline of the work is as follows:

The littoral zone is strictly limited to those portions of the shore lying between the average highest flood-tide and the average lowest ebb-tide of the month. Above this all deposits belong to the land surface, even though they may be in the form of low-lying deltas which perhaps once a year are flooded by the sea. Below the littoral zone all deposits belong to the general class of marine sediments, which may in turn be subdivided into estuarine, shallow open sea, and true deep sea.

It is pointed out that the sediments of the continental, littoral, and marine zones are accumulated under distinctive conditions which should frequently allow them, upon sufficient study, to be sharply separated. It is, moreover, concluded that, in comparison with continental and marine deposits, those of the littoral zone should form but a small fraction of the stratigraphic series, and that therefore, in the case of certain formations bearing marks of shallow-water origin and occasional exposure to the air, their frequent reference to an origin between tidal limits over the mud-flats of a shallow sea is inherently improbable, and should only be accepted where indubitably proven.

On the other hand, it is argued on inductive and deductive lines that an appreciable portion of the mechanical sediments incorporated into the geological record should have been made as subaërial delta deposits and therefore continental in nature, laid down in close association with the sea, and more or less interbedded with marine formations.

Besides these delta deposits, it appears that, taking the world as a whole, interior basin deposits, both of desert and pluvial climates, are now widely forming, frequently under favorable chances for preservation, and that such deposits should also occur to an appreciable extent in the geological record.[1]

Finally, it is concluded that the ratio of continental to marine sediments should have fluctuated widely through geological time. Following an epoch of continental uplift with mountain-making, the deposits formed in interior basins should attain a maximum, especially the deposits made under desert conditions. Accompanying this stage, piedmont alluvial deposits would be formed, largely temporary in character, since, upon the topography passing into the stages of maturity, they tend to be removed by the rivers which laid them down.

As the erosion verges toward maturity, subaërial delta-building, encroaching upon the shallow seas, would attain greater importance, since the amount of stream-dissection over the region of the headwaters increases; the streams, now being graded, carry the sediment through to the shores, and submerged continental platforms have had time to form. The greatest proportion of subaërial alluvial deposition should take place after epochs of mountain-making which have taken place without notable uplift of the continental platforms, as seems to have occurred several times during the Paleozoic. Since in that case a large portion of the river sediment is poured into more or less protected epicontinental seas, none of this portion reaches the deep ocean, and much of it forms a subaërial delta, since the seas are shallow and the wave-action weak.

Eventually, as the continent becomes topographically old, the mountain slopes become subdued, the burden of the rivers lessens and becomes more largely rock matter in solution. The rivers can no longer build out extensive deltas against the seas, and marine planation, aided by a slight elevation of the ocean surface, may cause

[1] While this article was being written, in December, 1905, a paper on "Torrential Deposits and the Origin of Sandstones and Conglomerates" was read by title to the Geological Society of America by Professor W. H. Hobbs, in which he argues for a much larger proportion of subaërial arenaceous deposits in ancient strata than has been recognized. This article the writer has not yet had the pleasure of reading. The recent volumes of Chamberlin and Salisbury, 1906, also place emphasis upon the importance of subaërial river deposits, especially in Cenozoic times.

the latter to widely transgress the base-leveled land. Therefore, in the topographic old age of a continent shallow-water marine deposits should attain a maximum.

This cycle of relations between continental and marine sedimentation is then applied to geological history, especially to the late Proterozoic and Paleozoic, and it is concluded from the general geographic relations of certain epochs, as understood at the present time, that notable subaërial deposits of river waste might be expected to occur within those particular epochs.

The preceding discussion prepares the ground for a second portion, concerned with the detailed consideration of the significance of mud-cracks in association with other features, as indicating the continental and alluvial nature of certain deposits. Since mud-cracks also occur in littoral deposits, the necessity for the preceding quantitative study is seen. It is concluded that, next to coal-beds formed *in situ* or an abundance of land fossils belonging to the animal kingdom; in association with certain other easily recognized features mud-cracks form one of the surest indications of the continental origin of argillaceous deposits. The structure is also seen to most commonly originate under climatic conditions where the other tests are apt to fail. It is not contended that mud-cracked littoral deposits may not also form, but it would appear that they should be relatively rare.

This conclusion stands in opposition to the interpretation given to mud-cracks in the standard textbooks, where they are ascribed to the drying of tidal flats and regarded as evidences of shallow seas; the flood-plain origin, if noticed at all, being given second place.

On account of this divergence from the prevailing interpretation, attention is called to the desirability of confirming or modifying the present conclusion.

Finally, the criteria developed as to the significance of mud-cracks are applied in detail to the Belt terrane of Montana and the Unkar and Chuar terranes of the Grand Canyon, both of late Proterozoic age. This furnishes an example of the use of the criteria, and at the same time draws conclusions in regard to the origin of these formations, which in general are barren of both animal and plant fossils, and therefore lack the usual guides for arriving at their origin.

It is concluded that the Belt gives an illustration of two sedimen-

tary cycles, each of which contains a strongly marked formation of mud-cracked red shales, the shales alternating with sandy strata, and both judged to have been deposited on the flood-plains of rivers whose deltas had gained over the subsidence, finally filling up and displacing the shallow epicontinental sea. The cycle is thus seen, not only to pass from arenaceous and argillaceous to calcareous formations and back again, but to pass from land to sea, and back again to land, the latter transition being marked, not by a plane of unconformity, but by subaërial river aggradation. Ancient land surfaces are not to be recognized alone by the work of erosion, but may be surfaces of sedimentation, and resemble in this respect the work more usually done within the domain of the sea.

In the Grand Canyon region it is concluded that at least a large part of the Unkar terrane, with its 6,830 feet of strata, was built up by subaërial aggradation as the delta plain of a large river exposed to a climate characterized by frequent seasons of desiccation alternating with seasons of flood. Thus the detailed examination of these late Proterozoic terranes confirms by largely independent reasoning the general expectation arrived at in the earlier part: notable amounts of continental deposits being here found collected in geosynclinal basins formed within the continental platforms during this area of wide land extension. The agreement of conclusions from the geographic and stratigraphic lines of approach is felt to strengthen the degree of probability that in these instances the indications as to origin have been correctly interpreted.

INTRODUCTION

As pointed out by Walther in 1893,[1] although all geologists are familiar with the occasional extensive deposition of land-waste upon the land as among the results of geological activities at the present time, yet the prevalence of erosion on the land and of sedimentation beneath the sea has governed the interpretation of nearly all ancient sedimentary deposits. It has ordinarily been accepted as a geological principle that ancient continental surfaces are only determined by unconformities, while, on the other hand, all sediments, unless obviously deposited by fresh waters as proved by their organic contents, are

[1] *Einleitung in die Geologie*, pp. 719, 720.

taken as indications of the presence of ancient seas. Numerous instances illustrating this tendency could be cited from the writings of the leaders of the science, but a single illustration will suffice. In 1893 Bailey Willis contributed a most valuable article to the *Journal of Geology*, entitled "Studies for Students: Conditions of Sedimentary Deposition." It is because of the originality and value of this writer's numerous geological articles in general, and of this one in particular, that it is chosen for illustration. In this article sedimentation is defined as follows: "Sedimentation consists of three sub-processes—sorting, distribution, and deposition. These are effected by waves and undertow, tides, winds, and oceanic currents."[2]

While lacustrine deposits could be included under this definition, it leaves no place for fluviatile sedimentation, and of course does not pretend to include sorting, distribution, and deposition by the wind. While it would hardly have been within the limits of this one article to have treated fully of these land deposits, yet it is noticeable that in the introductory pages no mention is made of them, and sedimentation is repeatedly referred to as pertaining to the sea, rock disintegration and decomposition to the land, while the streams are mentioned as the carrying agents which sweep the sediment to the sea.[3]

In the above-mentioned article the subject of marine sedimentation is ably treated, especially noteworthy being the dependence indicated between the relation of the sediments upon both the activities of the ocean and the topographic character of the land. The present article aims to treat of some of the general relations of marine and continental sedimentation, and to partially indicate how these relations may be expected to fluctuate with the extent, topography, and climate of the continental masses. It may be considered, therefore, as supplementary to the above-mentioned article on the conditions of marine sedimentary deposition.

As showing exceptions to this tendency to neglect the deposits formed upon the land must be noted the work of the geologists of the Indian survey for the past thirty years, and that of other geologists who have been most familiar with the Tertiary and Recent deposits within the interiors of Asia and America.

While the importance of land deposits has, during the past decade,

[1] Vol. I, pp. 476–520. [2] *Loc. cit.*, p. 480. [3] *Ibid.*, p. 480.

become more fully appreciated, it is nevertheless true that the greater part of the sediments comes to rest beneath the sea. Yet the fact that in the past the possibility of other modes of origin has not been sufficiently held in mind, throws doubt, in the opinion of some geologists, upon the interpretation of certain ancient formations consisting of unfossiliferous sandstones and shales.

Further, in regard to those deposits which are universally conceded to be of fresh-water origin, it has formerly been unconsciously assumed, without adequate proof, that the deposits were laid down in permanent bodies of standing water, and hence were lacustrine rather than fluviatile or æolian. To illustrate the important consequences flowing from such an interpretation, it may be mentioned that in all of the older American literature it was always confidently stated, without discussion of other possibilities, that the Tertiary was characterized in the Rocky Mountain region and over the Great Plains by enormous fresh-water lakes, larger than any in existence in the world today. Within a few years this view has been vigorously combated, and Matthew, W. D. Johnson, Haworth, Davis, and Hatcher have shown that the greater number of the Tertiary formations are better interpreted as the deposits of aggrading rivers wandering over broad flood-plains.

In view of the several modes of origin which are possible for shales, sandstones, and conglomerates, and the variable interpretations which have been sometimes given for a single formation, the writer, in that part of a lecture course upon advanced structural and dynamical geology which deals with sedimentary structures and their origins, has been accustomed for the past two years *first, to discuss the conditions of formation of sedimentary deposits*, as they are observed to occur at the present day in various continents and under various climatic conditions; *second, to compare the relative areal and volumetric importance* of the several kinds of deposits forming at the present time; *third, to discuss the probable changes in the relative importance* which may be expected to have occurred in the earlier ages, owing to such general movements of continental uplift and subsidence, mountain making, climatic change, etc., as are generally recognized to have characterized and individualized the preceding ages; *fourth, to give the detailed distinctions in composition, texture, and structure* by which

the several kinds of deposits may be distinguished according to their mode of origin; and, *lastly, to apply the foregoing principles to a few examples,* in order to illustrate their use, and to interpret the geography and climate of preceding ages.

In order to bring together the facts for such a discussion, it is only necessary to search the abundant literature of the past fifty years; but the writer has found no single article which presents the subject in quite this way, or arrives by this method at the conclusions to which he has come in regard to the relative importance of certain classes of deposits and their distinctive features. It has seemed worth while, therefore, to arrange portions of this in form for publication, omitting much which is necessary for class work, but which can be found ably developed in various books and articles, and enlarging on other portions which are not so fully discussed elsewhere.

For this presentation it seems best to give, first, an inductive discussion of the relative importance of continental, littoral, and marine deposits, as observed under process of present or recent formation, and to follow this by an abstract and deductive discussion as to the chances for the preserval in general of these several classes of deposits; and, finally, to close with another deductive argument as to the varying relative importance through geological time. This latter discussion should, however, be kept free from positive statements of opinion upon individual formations, in regard to which there may be doubt or difference of opinion; the purpose of the article being accomplished in merely opening the question as to what kinds of deposits should be expected to predominate, from the premises of our present ideas in regard to the geography and climate of past geological times. It would be suitable for a later article, however, to discuss in detail certain distinctive chemical, textural, and structural features characteristic of the several kinds of deposits, and to apply these to individual formations, thus confirming or disproving by an inductive process the preceding general conclusions arrived at by deductive reasoning. Only by a combination and confirmation of these two methods can safe conclusions be arrived at in interpreting the fragmentary remains of the results of unseen and now vanished processes.

Either inductive or deductive methods used by themselves are always liable to error, since we can seldom be sure that man has appre-

hended all of the essential factors which lead to a result. This is especially true of geological science, where the field of the unknown is so great, and where, for example, the past few years have brought forth facts in regard to Cambrian and Permian glaciation which have overthrown previous confident deductions in regard to the nature of Paleozoic climates. Deductive conclusions, especially, therefore, until confirmed by detailed study, should be offered as suggestive, rather than conclusive; to be tested by investigation before being finally accepted; but on that account they are none the less valuable.

The following article must therefore, as previously stated, be divided into two portions: first, an inductive study from observed facts as to the general relations of land, seashore, and marine sedimentation; and, second, the deductive application of the relation of these to the topographic cycle and to previous time. The last is to be taken as true only in a broad way, and with many possible exceptions; as suggestive rather than final.

THE IMPORTANCE OF CORRECT INTERPRETATION

Stratified deposits may be laid down either upon the land, beneath the sea, or in that transition zone known as the littoral, which by the ebb and flow of tides belongs alternately to the sea and the land. It is of fundamental importance in stratigraphic geology that land and sea deposits should be sharply distinguished from each other, as may be seen from the consequences which follow in attempting to outline the ancient geographies. On the one hand, if the formation is considered marine, it implies a submerged attitude to the land, a spread of ocean waters, a home suitable for the development of marine faunas, a barrier between lands—separating into distinct provinces the neighboring terrestrial faunas. On the other hand, if the formation is considered to be of terrestrial origin, precisely the opposite conditions are implied, the region now excluding the life of the ocean and serving for the support of land-dwelling types, and possibly offering means of communication between otherwise separated lands. The third alternative is to consider the deposits as transitional and belonging to the littoral zone, in which case the life is predominantly related to the sea, though invaded between tides by life from the land.

As oceanic, transitional, or continental, the region must be repre-

sented upon maps of the period; and thus in any restoration of the relation of land and sea of past times the paleogeographer is called upon to commit himself as to the origin of the deposit, with all of its far-reaching implications.

Even if the formation is considered as originating upon a continental surface, the problem of interpretation is not ended; for several alternatives remain to be considered: whether the deposit has accumulated within the confines of lakes, or has been laid down under humid climates upon aggrading river plains, or washed upon arid plains by intermittent floods, or, finally, accumulated by the action of the desert wind as loess or dune sand. To extend the illustration previously mentioned: Under the view that the Tertiary accumulations of the Great Plains and Rocky Mountain region in general were made in enormous fresh-water lakes, the Great Plains must have acquired later their tilted character, implying a more recent westward uplift of some thousands of feet. The mountainous plateau has consequently often been regarded as at that time low-lying and the climate moist. Under the contrary view, that the deposits are largely fluviatile or Æolian, the region may, however, be regarded as having been as greatly elevated and tilted then as now, and the climate on the whole as always semi-arid.

THE CLASSIFICATION OF CONTINENTAL, LITTORAL, AND MARINE DEPOSITS

The term "continental," as used by Penck and Walther, applies to all deposits upon the land, whether made by talus, creepage, by rivers, by lakes, or by the wind. The fact that they are made upon the visible surface of the continents and can show no relation to the sea is the only bond of union among these otherwise unrelated deposits. Each is marked by a certain assemblage of characteristics, which cannot be given in detail here, the most certain being the presence of fossils of an abundant fresh-water or land life, and an absence of marine. Where the deposit is unfossiliferous, there may frequently be doubt as to its continental or marine origin.

To marine or estuarine deposits belong all formations deposited in the ocean, or its outlying portions, below the level of the average of the lowest tides. Within this area, covering about three-fourths of

the earth's surface are laid down a great variety of deposits, varying from the oozes of the oceanic depths to the muds of protected bays or of epicontinental seas, and the sands and gravels which front the beaches facing the more or less open seas. It is only in regard to the detrital shallow-water deposits that serious doubt as to their origin is liable to arise, and it is only these, therefore, which need to be considered in the present connection.

Where salt or brackish water fossils occur in abundance, a possible continental origin is eliminated, and there will be expected also species which do not live within the zone of the littoral, thus proving the absence of a littoral origin. Where fossils are absent, the more uniform and widespread character of the deposit, the color, and other features, summed up by Walther,[1] may settle definitely the marine origin of an ancient deposit. The marine deposits are, however, as thoroughly characterized by the absence of most of those features which mark continental and littoral deposits, as by their own distinguishing features. Chief among these may be mentioned the absolute absence of mud-cracks, rain-prints, and the foot-prints of terrestrial animals.

To the littoral division belong, strictly speaking, only those deposits which are laid down between the limits of high and low tide. The term is frequently, however, rather broadly used as relating to the neighborhood of the shore. Thus one may encounter expressions in regard to dune sands of the littoral belt or conglomerate deposits as indicative of the littoral; yet dunes are entirely beyond the limits of the tides, and gravels may be laid down at some distance from the actual beach. The littoral zone, with its deposits, is regarded by Walther as related most closely to the land; but this is a view upon which a difference of opinion may be justly held, and the majority of geologists would doubtless decide that its affinities were rather with the sea.

For present purposes it will be necessary to define the littoral zone more exactly, and to sharply restrict its limits. It may, consequently, be considered as the zone embraced between the *average* of the *highest* flood and the *average* of the *lowest* ebb tides of the month. This means that, on the average, the highest portions of the littoral

[1] *Einleitung in die Geologie*, III. Theil, "Lithogenesis der Gegenwart."

zone will normally be flooded by sea water once every two weeks, while storms and extra high tides may flood still higher portions at longer intervals. The mechanical deposits of the littoral zone are apt to be extremely variable in nature, and the individual beds more limited in area than is the case either upon the land or under the sea. Muds rich in organic matter, and of irregular distribution and thickness, are the common deposits of lagoons; sands and gravels will be deposited in tidal channels and as off-shore bars, the strata showing current marks and cross-bedding. Cleanly sorted sands, gravel, shingle, and sometimes bowlders will mark the face of the outer beach.

The littoral zone is characterized, in common with land deposits, by ripple-marks, mud-cracks, rain-prints, foot-prints, and fossils of land animals and plants; in common with neighboring marine or estuarine deposits, by ripple-marks and brackish or salt-water fossils. As distinctive shore marks held in common by the littoral zone and the margins of lakes are wave-marks, rill-marks, and the shelving nature of the beach.

ORIGIN OF TENDENCY TO CLASSIFY LITTORAL AND FLOOD-PLAIN DEPOSITS AS MARINE

Although the littoral zone is seen to have a number of distinctive marks which separate at least the upper half of its limits from the marine area, it is regarded in the great bulk of geological literature as merely a border portion of the sea, and its deposits, except where beach structure is shown, are commonly thought of as marine deposits made in shallow water, and ordinarily at no great distance from the land. Mud-cracks, rain-prints, and foot-prints are frequently cited as evidence of mud-flats exposed at low tide and bordering the sea.

This close alliance of the littoral zone with the marine might be unimportant, were it not that the majority of the criteria which are relied upon as determining the presence of the littoral zone apply equally well to flood-plain deposits made upon the land at any distance from the sea. Furthermore, in periods of vigorous erosion river deltas may completely fill up shallow seas and receive large amounts of river sediments upon their upper surfaces; then by a slackening of erosion or an increase in subsidence, may frequently become submerged. In such a way river deposits bearing these features

common to the littoral zone may occur between truly marine formations. Thus, *first*, the perception of the principle that erosion dominates the land and sedimentation is largely restricted to the sea; *second*, the fact that in Europe and eastern America river aggradation is much less important that in many other regions; *third*, the confusion of littoral and flood-plain deposits ; and, *fourth*, the grouping of littoral with marine formations, render it probable that in the past certain unfossiliferous river deposits have been misinterpreted as marine or estuarine.

It is intended to show that the area of the zone of true littoral deposits is always a small fraction of the area of shallow-water marine deposits, and usually but a small fraction of the area of various forms of land deposition; that, furthermore, the chances for the preserval of littoral deposits is slight in comparison with those of either marine or continental origin, and consequently that, unless an ancient formation is clearly of littoral origin, it is more likely to be either marine or continental. For that reason it will be necessary to discuss the relative areas of deposition of the three classes of deposits, the characteristics which they hold in common, some of their distinctive features, and especially their relative chances for preserval.

THE REGIONS OF CONTINENTAL SEDIMENTATION

Formations made upon the land may be classified under several divisions, as follows:

Desert deposits.—Typically where the evaporation exceeds the precipitation and no outflowing drainage results.

Piedmont river deposits.—Built up by rivers or shallow lakes upon the foreland plains or piedmont belt fronting high mountain ranges.

Basin deposits of pluvial climates.—The deposits laid down by rivers or in lakes in down-warped basins, such as those of the Great Lakes, situated in continental interiors, but not necessarily associated with mountains. If a large river, laden with sediment, flows across such a region, a lake condition can hardly arise, but, on the contrary, a broad river plain is more likely to be found, constantly built up as subsidence takes place.

Subaërial delta deposits.—Where powerful and sediment-laden rivers meet the sea, especially if the latter is shallow and protected from

tides and storms, a delta is rapidly developed, a considerable portion of which is a land surface reclaimed by the river from the sea.

GEOLOGICAL IMPORTANCE OF DESERT DEPOSITS

To consider the areas occupied by each of the above divisions, it is to be noted that the arid regions at present cover about 11,500,000 square miles; that is to say, at the present time over one-fifth of the land of the world has no outlet for drainage to the sea.[1] Within these regions extensive sedimentation goes forward, the waste of the mountains filling interior basins, either by wash from the mountain slopes, by streams which sink within their subaërial deltas, or which may flow into shallow interior seas. By far the greater portion of the waste is laid down by rivers, owing to the vanishing of the water into the dry air and the porous soil. At such places the streams flow in channels, but not in valleys, and in time of flood spread in a thin sheet of water for miles over the desert plains. Instances of this nature has been noted by Davis in Turkestan,[2] and by McGee in the Sonoran desert.[3] In Australia large temporary lakes are formed during the wet season, which during the seasons of drought become arid and burning deserts.[4] At irregular intervals, sometimes extending over several years, the most arid portions of the interior will for a few days assume the appearance of a boundless, though shallow, inland sea.[5] The conditions are thus of rather widespread occurrence in desert regions for the formation of stream deposits, current-marks, and mud-cracks associated with river flood-plains and broad, level, sandy tracts and playas—features possessed in common with deltas of arid climates and the mud-flats of the littoral.

In topographic youth torrential deposits near the mountains, and finer alluvium in the central portions, may accumulate to great depths in the interior basins. In maturity the waste is more widespread, though over much of the region more shallow in depth, while in old

[1] Dr. John Murray, "Origin and Character of the Sahara," *Science*, Vol. XVI (1890), p. 106.

[2] *Explorations in Turkestan*, p. 54 (Monograph, Carnegie Institution, 1905).

[3] "Sheet Flood Erosion," *Bulletin of the Geological Society of America*, Vol. VIII (1897), p. 87.

[4] E. A. Petherick, Mill's *International Geography*, p. 615.

[5] C. H. Barton, Mill's *International Geography*, p. 580.

age, as Passarge has shown, a thin layer of sandy or gravelly waste[1] is almost universal.

Besides these features, chiefly made or modified by the work of water, it is well known that wind transportation plays an important part in desert erosion and deposition. Immense stony wastes, as the belt of the Sierran Hamada, may in this way have all soil removed, the finer dust being carried to great distances and ultimately out of the desert region, the sand being swept in the form of dunes over great areas of country; the dunes themselves, frequently hundreds of feet in height, being but the upper, wind-tossed portion of a deep deposit of sand. From the study of the surface of arid regions it would seem that a conservative estimate would arrive at the conclusion that at least one-half of the desert areas, and consequently one-tenth of the land surface of the world, is covered with more or less important deposits of recent desert accumulations, only a small portion of which are characterized by salt and gypsum. In interpreting desert conditions from the sedimentary record of previous ages, redness of formations, indicating subaërial oxidation, and roundness of sand grains, as indicating æolian action, and other features, are sometimes used; the presence of salt and gypsum is, however, the only characteristic which is determined at a glance and considered as a positive indication of an arid climate, and the only feature which is commonly used. But from the small proportion of present desert areas which are characterized by these deposits, and the great amount of land surface which is now desert, it would seem that the problem of ancient desert deposits should enter much more largely into geological history than is usually appreciated.

PIEDMONT RIVER DEPOSITS

Piedmont river deposits are built up in front of young and lofty mountain regions removed from the sea, by torrential rivers, which on escaping from the mountains are loaded with waste which they are unable to carry across the gentler slopes of the plains. As a region where such work is actively in progress at the present time may be cited the Pampas of northern Argentina. An early and excellent account of this region is given by John Miers, writing in 1825, who,

[1] Review by W. M. Davis in *Science*, N. S., Vol. XXI (1905), pp. 825–28.

although not a professional geologist or geographer, made many acute observations. His most significant statements in regard to the present topic may be quoted as follows:

> The rivers which flow from the Cordillera proceed only from the melting of the winter's snow, and bring down with them an amazing quantity of fine alluvial mud. In their long passage through the mountains, and for some distance after leaving them, the descent is so rapid that the great quantity of matter held in suspension cannot subside. The Tunuyan, for instance, even as far as Coro Corto, has as much mud in it as can be suspended in agitated water. This is the case with the water supplying Mendoza, which none of the people can drink without either filtering, or placing it for a long time in a state of quiescence; so surcharged is it that they are obliged every day or two to clean out their irrigating channels, which would otherwise be filled with fine sand. If we take into consideration the nature of the country to the southward, its long and almost imperceptible descent towards the ocean, the immense bulk of alluvial matter that must yearly be brought from the Cordillera, and which must somewhere deposit itself,—we cannot but conclude that the rivers which may once have flowed in deep and uninterrupted channels to the ocean, must, from such causes, have had their beds raised in progress of time to the level of the surrounding country: the continual shifting of their courses over level plains; the constant accumulation of muddy detritus, must have effected the gradual disappearance of navigable or continuous streams, and produced that series of swamps, and the kind of country, which, according to the most credible accounts, exists throughout the vast Pampa territory.[1]

In the case of rivers which run through to the sea this process of deposition comes to an end when they have built up this portion of their courses to the necessary grade, unless a geosynclinal warping takes place in front of, and in line with, the neighboring geanticline; in which case the rivers may still continue to build up an extensive plain with a slope of from 1 to 10, or even 30, feet per mile. This process will be favored when the area of the plain is deficient in rainfall, as is the case with the high plains of the United States and Argentina; since under such climatic conditions there is no added volume of river water to assist in carrying through to the sea the detritus obtained from the mountains. The same effect may take place, however, where the climate of the plains is humid, provided that the lessening of the grade is not fully compensated for by the added volume of waters.

[1] *Travels in Chile and La Plata*, by John Miers, in two volumes (London, 1826; C. Baldwin, printer), Vol. I, p. 113.

This is illustrated by the recent or subrecent alluvial deposits of the Ganges, fronting the Himalayas for nearly 1,000 miles, and maintaining a breadth of from 100 to 200 miles. The most western portion of this plain, as well as the confluent plain of the Indus, receives near the Himalayas between 10 and 30 inches of rain per year, and is relatively dry; but the greater portion of the piedmont Gangetic plain receives between 30 and 50 inches per year. In some ways, however, this plain is not a good illustration, since it graduates insensibly into the delta and is restrained by the plateau area to the south. In no place does it reach 1,000 feet above the sea, the highest elevation recorded being 924 feet above the sea on the low alluvial divide between the Ganges and the Indus.[1]

The Ganges system at the present time is probably eroding more than depositing, but must have built up the river-plain in the past. Nearly the whole area, however, of the Brahmaputra valley, in Assam, a region of heavy rainfall, is occupied by the newer alluvial deposits, and hence must be in the process of piedmont valley-building.[2] Similar important deposits of river conglomerates, sands, and clays of Oligocene, Miocene, and Pliocene age are found on the northern slopes of the Pyrenees and Alps, where the climate was presumably as humid as at present, but the intercalation of marine strata among these indicate a low-lying condition and a proximity to the sea, so that the sediments are probably as much of the nature of delta deposits as of piedmont slopes of waste.

In estimating the areal extent and importance of such piedmont waste slopes of continental interiors, it is to be noted that their extent in the western United States, in Argentina, and in India may be taken as roughly equal in area to that portion of the lofty mountain region from which they come. Such deposits would, of course, be ultimately eroded in a later stage of the same topographic cycle which witnessed their production, were it not that downward warping in front of a mountain axis is a not uncommon incident, allowing a progressive accumulation of waste, and protecting the lower portions from ultimate erosion until some reversal of the geological activities occurs. Owing to such downward warping before the later upturn-

[1] Medlicott and Blanford, *Geology of India* (1897), p. 391.

[2] *Ibid.*, p. 396; Mill's *International Geography*, p. 475.

ing, some 14,000 feet of river deposits were laid down in the Siwalik formation of the Upper Tertiary in the northwest Punjab.[1] In searching the past for similar deposits, from the nature of their origin they need be looked for only upon the ancient mountain forelands, and only after periods of orogenic revolution.

BASIN DEPOSITS OF PLUVIAL CLIMATES

The basins of the Great Lakes may be taken as good examples of down-warping in continental interiors. Formerly regarded by many as largely owing their origin to ice-erosion, they are rather looked upon at the present time as chiefly due to crustal warping, somewhat accentuated and scoured clean by the Pleistocene glaciation. Their recency, and the fact that no rivers laden with detritus from mountain regions flow into them, cause them to be still unfilled and their basin nature to be clearly apparent. It would seem that such basins are not unique, but are rather constant features of the continental platforms. In times of diminished land surfaces and lessened erosion these may be connected with the oceans and exist as epicontinental seas. In times of wider continental extension and increased erosion they are likely, if shallow, to soon become completely filled with sediment, after which rivers will flow through them on their way to the sea. In this event only a geological study of the region may demonstrate the basin-like structure of the underlying basement.

Perhaps the most conspicious examples of interior continental basins receiving large quantities of river sediments at the present time are to be found in South America. The Brazilian plateau, like an island, is surrounded on all sides by a wide lowland, at no place more than 650 feet above the level of the sea. The headwaters of the Paraguay and the Guapore, the latter one of the southernmost tributaries of the Amazon, with hardly 4 miles between them, are often covered by the same floods.[2] The greater portions of the great river valleys of South America are underlaid by Tertiary deposits, and the superficial formations are of recent origin.[3] This is indicated by any good map, where it is seen that the central basin of the Amazon possesses braided rivers, lagoons, and unexplored distributaries connecting

[1] Geikie, *Text Book of Geology*, 4th Ed., p. 1297.

[2] J. Batalha-Reis, Mill's *International Geography*, pp. 865, 866.

[3] *Ibid.*, p. 867.

them, the whole, from the geographic descriptions, constituting a more or less perpetually flooded and impenetrable tropical forest jungle. This great basin is largely shut in on the east by the uplands of Guiana and Brazil.

A similar physiographic condition is graphically described by Mr. H. H. Smith as characterizing the headwaters of both the Madeira and the Paraguay.[1] These streams in their upper portions flow through more or less separate and inclosed basins. The upper Paraguay rises 30 feet annually. All the flat lands above the Fecho dos Morres to Villa Maria—over 400 miles in a direct line—are subject to river floods, and these are deepest toward the north. The width of the flood-plain at the mouth of the Sao Lourenço can hardly be less than 150 miles from the rocky lands on the east to the base of the Serra dos Dourados. The whole region is a labyrinth of lakes, ponds, swamps, channels, and islands in a grassy plain, the only forest being near the river. Even at low water one-fourth of it is flooded; when the river is at its highest, the whole plain is a vast lake, covered with floating grass and weeds.

The South American instances illustrate most fully the manner in which large interior basins may be filled with river sediments. Usually the process of aggradation is not so striking and rapid. Where the down-warping is of minor importance, as in the central plain of Hungary, fertile and habitable plains may occur. Where the down-sinking of the crust has been deep and far more rapid than the infilling by the rivers, large interior seas may result.

Europe is largely surrounded, and separated from the other continents, by a series of such interior basins, but the dividing bridges are so low that they let in the ocean waters, and on the southern side all but the Caspian and Black Seas are united into the Mediterranean. Of these basins the upper Adriatic, the Ægean, and the Black Seas have witnessed great changes since the Tertiary, and Suess[2] regards the formation of the Ægean and Black Seas as even post-glacial. Previously to this recent down-sinking, fresh-water deposits were formed over the site of the Ægean, and still remain on certain islands in the

[1] J. B. Hatcher, "Origin of the Oligocene and Miocene Deposits of the Great Plains," *Proceedings of the American Philosophical Society*, Vol. XLI (1902), No. 169.

[2] *Das Antlitz der Erde*, Eng. trans., Vol. I, pp. 344, 345; also Plate V, opp. p. 463.

sea. The ability of large rivers to maintain land surfaces over sinking areas may be illustrated by taking a hypothetical case. Choosing Lake Superior, since it is the largest body of fresh water in the world, and the Mississippi-Missouri river system as a type of the greater rivers of the globe flowing from regions of rapid erosion, it may be computed how long it would take the Mississippi to fill the Lake Superior basin with sediment. Taking the annual discharge of the Mississippi, according to Humphrey and Abbot, as a mass of sediment sufficient to cover one square mile 268 feet deep, and again taking the area of Lake Superior as 32,000 square miles, and the average depth, derived from the contours of the bottom, as 550 feet, it may be readily computed that the Mississippi would fill up the basin in approximately 66,000 years. Therefore, if such a basin should originate in the path of a great river bearing a quantity of sediment equal to that of the Mississippi, it would only show at the surface during its subsidence as a somewhat swampy alluvial plain, without a distinct lacustrine stage, unless the movement of subsidence was irregular or the entire depression originated in less than 66,000 years. It is not probable that the majority of epicontinental basins originate as rapidly as this, indicating the conclusion that in periods of high land relief and rapid erosion river deposits, rather than those of lacustrine or marine origin, may be expected to fill the down-warpings within continental areas, and to a lesser extent those which are marginal. On the other hand, Forshey has computed that it would take the Mississippi 11,000,000 years to fill the Gulf of Mexico with sediment, providing that the bottom did not sink under the load; and this points the contrast between the relatively small and shallow epicontinental basins and the true oceanic gulfs or mediterranean seas.

In conclusion, it is seen, then, that interior basins may be divided into two classes, the shallow and the deep. The former, if within the reach of important rivers, may be maintained as a continual land surface, the basin nature being not conspicuous; the latter will more usually form true mediterranean seas. Basins of these two classes occupy appreciable portions of the present continental surfaces, and doubtless have frequently been as important in the past. The shallow warpings still belong to the continental platforms, and their deposits, either fluviatile, lacustrine, or marine, are frequently exposed

by erosion; but it is doubtful to what extent such deep downbreakings as those of the mediterranean basins are ever restored to the surface of the land, and their deeper deposits consequently opened to observation, the most favorable chance being where the region becomes involved in a later mountain revolution. Whether or not the deposits of the shallow basins are continental or marine will depend upon the vigor of stream-erosion, the rapidity of subsidence, the breadth and height of the surrounding lands, and nearness or distance from the sea. As epeirogenic and orogenic movements have been intermittent and variable in nature, the continental or marine infillings of such basins will thus have varied largely through geological time.

DELTA DEPOSITS

A delta may be divided into two chief portions, one of which, above the water, forms a low land surface, usually fertile and densely inhabited; another portion being deposited beneath the sea, and building forward the front of the delta. As is well known, borings in the Mississippi, Ganges, and Po deltas have revealed fresh-water fossils and beds of vegetable matter at some hundreds of feet beneath the present level of the sea. Such facts have led to the view that large delta surfaces are frequently regions of subsidence, and that they may be maintained above the sea-level by the continual deposit of river material. Thus it is seen that delta formations are divided into portions which are continental, littoral, and marine.

The possibly subaërial delta origin of certain ancient formations has been long since suggested; to cite a single instance, as far back as 1886, Bonney, in his presidential address before the British Association, concludes that the English Bunter is probably a subaërial delta formation, analogous to the Siwalik deposits of India.[1] Notwithstanding such instances, however, it will probably be admitted by most that, in interpreting the mechanical deposits of previous ages, especially where these are thick, barren, and suggestive of discharge at the mouths of large rivers, usually no adequate discussion has been given as to the possible intermingling of subaërial and submarine portions. The section at one place may represent wholly the land-surface deposits; at another, the wholly off-shore zone; and at still

[1] *Report of the British Association for the Advancement of Science*, 1886, p. 618.

another, an intercalation of subaërial and submarine strata. As an illustration may be cited discussions regarding the Neopaleozoic deposits of the eastern United States. The interpretation has usually been that of river sediments distributed over the bottom of a shallow interior sea, in which subsidence took place *pari passu* with sedimentation, so that occasionally mud-flats or marshes became exposed; but subaërial delta surfaces are hardly considered, and the region is held to have been essentially a permanent sea, so long as sediments of the time were formed.

Of course, where marine fossils occur, there is no question of the presence of ocean waters, and, on the other hand, at times of coal-formation there is no question as to the presence of a delta swamp; but in regard to the great volume of more or less completely unfossiliferous detrital deposits the interpretation has usually been one of marine origin, without an adequate consideration of a possibly subaërial delta nature; and this sometimes in spite of the fact that mollusca are found whose habitat seems indicative of non-marine waters, as, for instance, Amnigenia of the Upper Devonian.

The deposits of the present, as Walther has noted, are studied in horizontal plan; the deposits of the past are studied in section. It is to indicate from present delta-building the vertical relations which are to be expected in ancient deposits between the continental, littoral, and marine portions of the delta, that a considerable discussion seems necessary.

RELATION OF DELTAS TO REGIONS OF SUBSIDENCE

The ratio of these three portions to be anticipated in the stratigraphic record will depend largely upon the conception of the part which subsidence of delta regions plays, as a usual, or merely an occasional, accompaniment of the process of delta-building. As facts bearing upon the question, may be cited the presence of fresh-water deposits within a number of the present larger delta regions at levels beneath the surface of the sea. Again, periodical flooding of the delta surface is evidence of land deposition going forward at the present time, while rivers intrenched, and never overflowing the plains formerly built up by their agency, are evidence that aggradation has ceased, or even that degradation has begun. Taking a general view

of river characteristics, it is seen that at least in North America piedmont slopes of alluvial waste are now frequently undergoing dissection, but that the great delta regions, such as those of the Mississippi and the Colorado, are receiving annual accessions of fresh-water deposits. In many cases, especially on the eastern coast, subsidence has been so recent that the rivers have only begun the work of filling their embayed valleys, and notable deltas have not yet been constructed. On the whole, however, the work at the river mouths stands in contrast to that of their middle and upper courses. Extending the view to the greater rivers of the world, it would seem to be a safe conclusion that, as a rule, they are building up their flood-plains, even if not encroaching upon the sea.

The problem next following is whether this is due to a local stationary attitude, or even subsidence of the delta regions, or to an average general stationary attitude or subsidence of the lands as a whole. In answer to this general problem there appears to be no unanimity of opinion. The continental margins frequently show drowned coastal shelves cut across by river gorges, but this is no indication as to the character of present movements. In Andrée's *Hand-Atlas*, p. 4 (Leipzig, 1904), movements of elevation are indicated as taking place at the present time at many places along the shores of all continents, while movements of depression are indicated only along the eastern coast of North America, the coasts of France and the Netherlands, the eastern shore of the Adriatic, the delta regions of the Nile and Amazon, and more than half of the oceanic islands. While there are undoubted errors of detail in this map, it may be assumed as a first hypothesis that the general result is true, and that the continents at the present time are in a general stage of upward movement; or, perhaps speaking more correctly, the oceans, by the subsidence of their basins, are receding from the lands.

If this conclusion be true, the subsidence of regions of sedimentation at the present time is probably less conspicuous than in the average of past time, since it is only where the local downward movement is more pronounced than the general regional upward movement of the lands that actual subsidence would result.

Turning from induction to deduction, subsidence of deltas as distinct from the surrounding regions is to be anticipated only where the

load of sediment is sufficient to lead to isostatic readjustment, or where the river debouches into a natural geosyncline. That such subsidence was common in ancient geosynclines is accepted on the evidence of shallow-water formations accumulated to a thickness of many thousand feet, and whether the formation was made slightly below or above the water surface would apparently have but little influence upon the movement of subsidence. Again, in periods of quiet the erosion of the lands, as Chamberlin has shown, would tend to lift the level of the sea and lead to an apparent subsidence of all delta regions to the extent of some hundreds of feet from this cause alone. Further, the drainage of the continents is, in general, away from the geanticlinal regions and toward the geosynclinal areas. The land-waste is carried in both directions from the geanticline across the stationary tracts, with the exception of those receiving piedmont deposits, and is thrown down by the river in crossing some region of subsidence, or upon meeting the ocean upon the continental shelf or at the margin of the continental platforms. Usually the waste from at least one side of the geanticline must be carried a considerable distance before passing beyond the limits of the continental platform, and the chances are frequently good for deposition before reaching that limit.

Where a geosyncline or epicontinental sea is encountered, the sediment will accordingly be concentrated; and even if the load of waste should not have any influence in leading to isostatic down-sinking, these areas would still be characterized as the great catchment basins of sediment deposited upon the continental platforms; the most favorable situation being that illustrated by the Great Valley of California, where a trough exists between mountain ranges, and the waste naturally gravitates into it; the least favorable being found in such isolated basins as those of the Great Lakes, far removed from any considerable mountain range. There is therefore frequently, but not necessarily a sympathetic relation between regions of subsidence and the discharge of great rivers, with their load of sediment.

From these lines of reasoning it may be accepted that the portions of the continental platforms occupied by the mouths of the larger rivers have frequently been through past time regions of subsidence, with consequent river aggradation; but the strongest evidence for

this conclusion is not obtained so much from the nature of present movements as from the evidence of the upturned and eroded strata themselves, deposited as the geosynclinal axes sank.

Where there is no subsidence, as is to be expected in the case of the smaller deltas, the subaërial character is readily maintained and extended as a result of delta-building, but the subaërial deposits cannot extend below the water level. Where subsidence accompanies sedimentation, however, the subaërial character of the delta tends to be destroyed; but if the river is able to build its plain upward as fast as the downward movement takes place, the subaërial deposits may reach to any depth. In the larger deltas which have been tapped by boreholes this appears to be the case.

FACTORS GOVERNING DELTA LAND SURFACES

The strata of a delta have been classified into the bottom-set, foreset, and topset beds;[1] the first consisting of fine material deposited from suspension on the bottom of the sea beyond the main portion of the delta, the foreset beds comprising the steeply inclined portion consisting of slightly coarser detritus, and the flat topset beds being the result of the aggradation work of the river, building up its stream to grade as the front of the delta advances farther outward, or as the whole slowly subsides. The topset beds are largely of subaërial origin, though the delta is fronted for a short distance by a shallow submerged platform, across which the detritus is carried to deeper water. Of these three portions, the foreset beds usually comprise the greater *volume* of the deposits, but the thinner bottomset and topset spread over the greater area.

The ratio of the submerged to the emerged portions of the topset beds depends upon a number of factors. A rapid subsidence may carry the whole beneath the sea, but *where subsidence is slower than upbuilding*, the proportion of the topset surface which is submerged will depend upon the balance of power between the waves, tides, and currents on the one hand, and the constructive work of the river on the other.

The depth of water over the submerged portion of the delta also depends upon the strength of the waves. Thus, an inspection of maps

[1] Chamberlin and Salisbury, *Geology*, Vol. I, p. 191.

possessing bathymetric contours shows that the Amazon, facing the open ocean, and subject both to wave-erosion and tidal scour, has a submerged delta which for 200 kilometers is less than 20 meters beneath the surface of the sea, while the aërial portions belong rather to the flood-plain, since they do not extend eastward beyond the adjacent margins of the continent. On the contrary, in the case of the Nile, the Danube, the Po, and the Mississippi, flowing into relatively quiet and tideless seas, practically all the foreset beds are above water, and thus the greater part of the *area* of the river delta, neglecting the attenuated bottomset beds, is a region of subaërial—that is, of continental—sedimentation.

According to Forshey

> more than two-thirds of the Mississippi delta in the ordinary state of the river are above water. . . . . But if the river were unrestrained by levees, the highest floods would fill the alluvial basin and make a sea 600 miles long, 60 miles in mean width, and 12½ feet in mean depth.[1]

As another illustration,

> the delta of the Hoang Ho (Yellow River) extends along the coast from near Peking, on the north beyond the Pei Ho, to Hung-tse Lake on the south, where it joins the plains of the Yang-tse-Kiang. The distance is 400 miles, but the mountainous province of Shan-Tung is to be excluded. From the coast the delta extends westward for 300 miles. The river is here useless for navigation. The whole delta region would be under water during flood seasons except for drainage by artificial canals and dikes of great length.[2]

Under natural conditions every flood would, by the settling of mud or sand from the broad flood-waters, contribute to the upbuilding of the delta plain; as, for example, the statute of Rameses II at Memphis has been buried in about 9 feet of river deposit in somewhat over 3,000 years. The interference of man has, however, doubtless here changed the natural rate.

The geological importance of this aggradational work of rivers over their deltas is obvious. During periods of rapid subaërial denudation an appreciable volume of the sediments removed from the interior of the land should be laid down, not beneath the sea, but as a land surface facing and encroaching upon the salt waters. Such a character of river deposition would be at a maximum in a shallow

[1] J D. Dana, *Manual of Geology*, p. 197; quoted from C. G. Forshey, 1873.

[2] *Ibid.*, p. 198.

epicontinental sea, protected more or less effectually from ocean currents and possibly from tides; a sea which for that reason would be unable to cut away the rapidly forming deposits of the encroaching delta. Such a sea existed over much of the northeastern portion of the United States during much of the Neopaleozoic times. Within this basin of sedimentation former shallow-water conditions are indicated in certain formations by mud-cracks and supplemented by ripple-marks, cross-bedding, and inconstancy of arenaceous strata. This must signify that the upbuilding power of the ancient rivers was, on the whole, equal to or in excess of the progressive subsidence of the basin. There is not likely to be long maintained an exact balance between the two, and hence in general it may be said that such structural feeatures indicate a capacity in river-building to more than compensate for the progressive subsidence of the geosyncline. But, having granted this excess of sedimentary power, it is seen that, especially in the protected bays, the surface of deposition should be very largely a land surface; occasionally flooded, as a result of the rainy seasons, by the fresh waters from the land; occasionally flooded over the seaward portions during combinations of storms and high tides by the waters of the sea.

Diagrams illustrating the relations of foreset and topset beds under ideal conditions are given in Figs. 1 and 2. In Fig. 1 a delta is supposed to be built out into a quiet lake with constant water-level. The thicknesses perpendicular to the planes of stratification of the foreset and topset beds will vary approximately with the angle of dip of each. The ratio of volumes will depend upon the area multiplied by the thickness, and although the topset beds under these conditions may not be more than one-tenth as thick as the foreset beds, their area in a large delta, especially in a shallow sea, may be ten times that of the latter, so that the volumes of sediments deposited above and below the sea may be of the same order of magnitude. In Fig. 2 a *subsiding* delta is supposed to be built upward and outward, with just such speed that the front of the delta is maintained at a constant line. In this hypothetical case the gradient of the delta would be less than in the first case, the currents more sluggish, the delta more frequently flooded, and a greater proportion of the waste would be dropped upon the topset surface. Under such conditions the topset beds might

equal or exceed in thickness the foreset beds. Where the area of the delta becomes as great as was the case of the Carboniferous coal swamps of the eastern United States, the resulting volume of land deposits may far outweigh the volume of the foreset beds building the delta front.

At first thought it might be supposed that over a subsiding delta region the only effect would be an encroachment of the sea, without

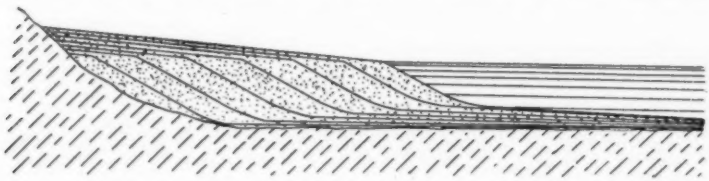

FIG. 1.—Ideal section of delta built out into quiet water of constant level.

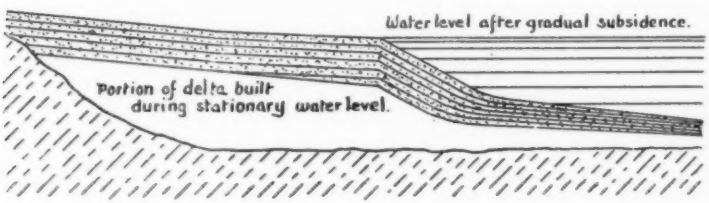

FIG. 2.—Ideal section of delta built out into quiet water when subsidence just balances deposition, resulting in a stationary shore-line.

changing the slope of the delta surface, diminishing the subaërial portion without increasing the rate of river deposition upon it. When a dam is thrown across a stream, however, and the water-level artificially raised, the gradient is flattened, and the stream made more sluggish for some distance upstream at levels higher than the upper edge of the dam. Where similar elevations of the water-level occur through natural causes, it is presumed, therefore, that the effect would result in an enlargement of the zone of fresh-water morass and increased river deposit, as well as a tendency to restrict the margin of the delta.

It is probable that many deltas reach a point beyond which they advance but slowly. This occurs in those fronting large bodies of

water, and exposed to heavy tides and storms. For example, Tremenheere has shown that detritus from the Indus is swept northwestward along the coast beyond the limits of the delta by the winds of the southwest monsoon.[1] The monsoon winds of the Arabian Sea are reversed during the year, with a resulting reversal of ocean currents; and this exposure of the delta front to the alternating and powerful waves, tides, and currents is doubtless the cause of the fact, made known by Murray, that terrigenous deposits extend 800 miles from the mouth of of the Indus and cover an area of more than 700,000 square miles.[2]

Under such circumstances the materials which in a quiet sea would contribute to make the foreset beds and advance the delta must be largely swept along shore and out to sea, contributing to widespread bottomset beds.

Excluding these widespread portions from the delta proper, it is seen that under these conditions the topset beds of subaërial origin, while not contributing a larger volume than before, may form a larger ratio of the entire delta deposit. On the other hand, as the delta advances into deeper and open water, a larger amount of material is deposited beneath the surface on the delta front, in order to build it out; and this also would cause the delta to advance more slowly, but diminish the ratio of the land-formed deposits. When a delta has reached a stationary limit, it is only possible for superficial deposits to be deposited through subsidence; but as this appears to be not unusual to such areas at the present time, it is also to be expected in the past.

The diagrams, furthermore, indicate that the ratio of subaërial to marine deposits in an advancing, but not subsiding, delta depends for one factor upon the relative gradient of the topset to the foreset beds. The gradient depends upon a number of factors which cannot be fully discussed here, but it may be mentioned that a river carries the greater amount of its burden in times of flood, and that those are the times when it also overspreads its flood-plain. From the broad and shallow flood waters much material is thrown down, more being

[1] "On the Lower Portion of the River Indus," *Journal of the Geographical Society*, Vol. XXXVII (1867), p. 77.

[2] "Marine Deposits in the Indian, Southern, and Antarctic Oceans," *Scottish Geographical Magazine*, Vol. V, No. 8 (August, 1889), p. 420.

deposited the shallower the waters, since the bottom velocity becomes less for the same surface gradient.[1] A broad delta, unrestrained by valley walls, unless these valley walls themselves furnish sediment, is therefore advantageous for surface deposition. The same may be said of deltas covered with vegetation, since Lyell long since pointed out from observations on the Mississippi delta the effectiveness with which vegetation entangles the sediment of flood waters. Coarseness and abundance of material, signifying rapid erosion at the headwaters of a river, are likewise favorable for subaërial deposition on a steeper gradient.

Summing up the foregoing discussion, it may be said that moderate subsidence, originally shallow and quiet seas, broad and long delta areas, and the presence of not far-distant mountain uplifts are all favorable to a large proportion of subaërial delta deposition. In addition, periodical floods over an arid delta region, and dense vegetation over a humid one, work to the same end.

While there is probably not sufficient data at hand to give quantitative expression to these statements, and indeed they must vary for every example, it may still give definiteness to thought to attempt to express in figures the ratios for the several classes of delta deposits. James Ferguson, quoting F. Prestage, states that in 1861 careful simultaneous experiments were made as to the quantity of solid particles held in suspension in the waters of the Matabangah (one of the distributaries of the Ganges): first on leaving the Ganges, where it was found to be 1 in 294 parts; while nearly at its junction with the Hoogly the quantity was 1 in 884, proving that two-thirds had been deposited *en route* in that short distance of not much over 50 miles in a straight line, though much longer by the meandering river.

In answer to the question as to how much of the entire Ganges alluvium is deposited upon the delta, and how much is carried to sea, Ferguson points out that during the cold weather, when the rivers are low, almost all of their silt will be carried to sea; but then the quantity of water is small, and that little comparatively clear. At the height of the inundation, when the river is overflowing its banks, at least one-half is deposited inland.[2] It is also pointed out that up to

[1] J. J. Rèvy, *Hydraulics of Great Rivers* (London, 1874), p. 147.

[2] "On Recent Changes on the Delta of the Ganges," *Quarterly Journal of the Geological Society*, Vol. XIX (1863), pp. 350, 351.

early in the eighteenth century the Brahmapootra joined the Ganges some 60 miles above the present junction, and that for a century later the Brahmapootra probably deposited nearly all its load of sediment in filling up the shallow back-water lakes across which its new course was taken. These lakes and swamps, having been bridged over by the date of writing, Ferguson was of the opinion that the delta face would be built outward with comparative rapidity in the place where it was then deficient.[1]

Thus the ratio of land and marine deposition is variable even on the same delta, with the season and in longer cycles. From various descriptions, however, the present writer would, as his impression, estimate that possibly in the case of large rivers from 30 to 50 per cent. of the material reaching the sea is sufficiently fine to be borne beyond the steep delta front, deposited as widespread blue muds, and forming the bottomset beds. These are largely spread at the present time beyond the limits of the continental platforms, and, where deposited at equal depths during preceding periods, have not entered to that proportion into the structure of the present continental surfaces, but still largely lie beneath the sea. Of the remaining 70 to 50 per cent., possibly from two-thirds to three-fourths has been deposited beneath the water, and from one-third to one-fourth as topset beds laid down upon the land. It is unnecessary to repeat that no value must be attached to these estimates. At any one time, however, the *area* of the land-formed portion is a much greater ratio the discrepancy between area and volume being due to the fact that the subaërial beds are thinner, and a given thickness requires a longer time to form.

In closing the topic, the problem of the unfossiliferous nature of many ancient deposits apparently well suited for the preservation of fossils may be mentioned.

It may be questioned as to why, if certain formations were deposited largely upon land surfaces, those surfaces were not overgrown by vegetation, preserved as carbonaceous deposits. To this it may be answered that other factors, such as climate, enter into such a problem, and that it may equally well be asked: How is it, if these strata belong to the littoral or the shallow sea, that fossils common to those zones

[1] *Loc. cit.*, pp. 332, 333.

of life are not present throughout? Here again various factors enter external to the present subject, which cannot be discussed without too much digression. It may be said in closing, that the absence of fossils leaves the origin of the formation in doubt, and that an unfossiliferous formation may have originated either on the land or beneath the sea. Certain structural criteria which may frequently throw light upon this question will be discussed in a following part.

SUBMARINE TOPSET DELTA DEPOSITS

In connection with the discussion upon the subaërial part of the delta, some mention has necessarily been made of the submerged part of the same, but more especially the steeply inclined foreset beds. Under the present head it is intended to discuss particularly the shallow, submerged portion of the delta in some detail, in order to show what relations it holds under various conditions throughout the world to the emerged portions of the same.

Relation of Waves and Nature of Deposit.—The proportion of the topset delta surface above and below water will depend upon several factors. Two of the more prominent are the rapidity of the

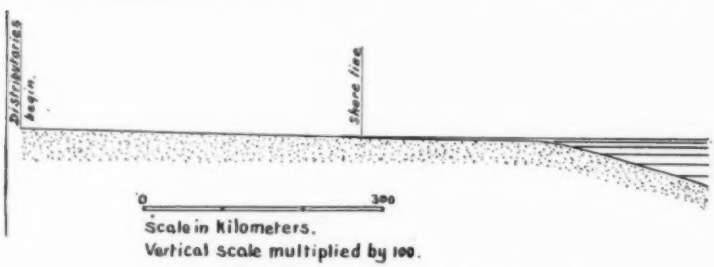

FIG. 3.—Profile. Delta of the Rhone in Lake Geneva.

deposit and its coarseness on the one hand, and the power of the waves on the other. The maximum of land topset beds may therefore be seen in such instances as Lakes Geneva and Constance, but especially the former, where the gritty sediment of rapid and loaded streams is confined closely between valley walls and discharged into the relatively quiet waters of a lake. The fact that practically all the upper surface of the delta is a land surface in the case of Lake Geneva

is shown by the section (Fig. 1) plotted from the bathymetric contours shown in Andrée's *Hand atlas*.

Turning to deltas which show a greater or less frontal submergence, the submerged portions are observed to lie either within or without the outer limit of the general coast-line, as determined by the offshore reefs. Such important shallow submarine delta platforms lie in front of and completely beyond the limits of the land in the case of the great Chinese rivers and the Amazon. In these instances the development of the submerged delta surface may be due in part to the fineness of the river deposit, allowing the sediment to be largely flooded out to sea in the fresh river water, as it spreads over the salt water below. On the other hand, the waves, tides, and currents are important and aid in cutting back the land surface by marine planation, the land material being swept by the undertow to seaward into the gradually deepening water. Thus in any particular case a certain equilibrium tends to be maintained between the continental and marine portions of the delta surface—an equilibrium which is especially liable, however, to be temporarily destroyed by irregular movements of subsidence or upheaval, since a small vertical movement will transfer the beach-line a long horizontal distance across the almost level surface.

Effect of Variable Point of Discharge.—In the above instances the delta surface is sharply divided into a land and water portion, and the littoral zone is at a minimum.

In another class of cases, illustrated by the Mississippi delta and the combined deltas forming the Netherlands, the deltas inclose within their outer land limits considerable bodies of shallow water or brackish lagoons, as the Mississippi and Chandeleur Sounds, and the Zuider Zee. In these cases it is observed that a large amount of sediment is discharged at one or two separated points over an extended delta coast-line, building out the delta at those places. The waves, drifting the material laterally, throw up barrier beaches, and shut off more or less completely large bodies of water, which thus lie within the front limits of the land delta. Usually it is only a matter of a few centuries at the most until the river abandons its built-out mouths and turns into the intermediate lagoons, as the Mississippi has been known to do near New Orleans, breaking through its levees in times of flood

and pouring into Lake Pontchartrain. Such a course would possibly before this have become permanent, had the river not been restrained by artificial means. Even in these cases, however, of land-protected sounds and lagoons, it is to be noted that the area of mud-flats exposed between tides is much less than the areas permanently covered by lagoon waters.

A river possessing a broad land delta, and shifting across it periodically, will thus build up a delta formation whose seaward portions will embrace an alternation of marine or lacustrine and fluviatile deposits. Farther inland the deposits will be entirely fluviatile.

Effect of Variable Water-Level.—Another condition which must normally modify the relations of land and sea in delta-building is that of changing level, resulting either from those variations in the water-level to which inland seas are peculiarly liable, or from irregular vertical movements, usually of subsidence, such as are known to be characteristic of regions undergoing sedimentation.

Interior seas.—The case of inland seas is illustrated by the delta of the Volga, shown in cross-section in Fig. 4, and which may be

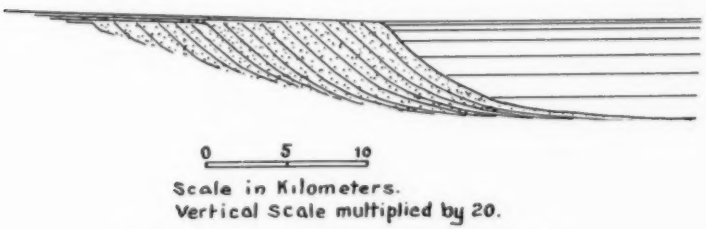

FIG. 4.—Profile. Delta of the Volga in the Caspian Sea.

contrasted with Fig. 3. A good map shows that the entire northern portion of the Caspian Sea, lying chiefly east of the line of the section, is but from 1 to 11 meters deep. Such an extended shelf to an inland sea facing two large rivers cannot reasonably be ascribed to wave planation of the river deltas, nor, on comparing this shelf with other deltas, can it be supposed that waves in the absence of tides and currents could have transported the land-waste to such a distance from the river mouths.

It seems certain, then, that the present submerged shelf was

developed as a land surface, and presumably by river-building rather than by river erosion. In confirmation of a former lower level of the Caspian Sea, Walther quotes the record of a boring on the shore of the Caspian southeast of Krasnovodsk, in which dune sands were found to a depth of 35 meters;[1] and more recently Davis has noted the evidence of a low-water epoch between the Tertiary and Quaternary periods of Caspian expansion, as indicated by the stream-eroded character of the present shores at Baku, which must have endured for a much longer measure of time than that of the Quaternary high-water stage and the present mid-water stage taken together.[2] Davis does not correlate the low-water stage with the development of the present submerged shelf, but unless crustal warping has materially disturbed the relations, it would seem a not unnatural correlation.

Not only are interior seas thus liable to long periods of expansion and diminution, resulting in an alternation of fluvial and lacustrine deposits, but cycles of shorter period, though enduring for centuries, may be superimposed. Thus Huntington has recently presented the evidence for a working hypothesis that the Lake of Sistan has passed through at least ten fluvial epochs during the Quarternary era;[3] the fluvial epochs being marked by widespreading floods over temporary playas, leaving pink beds of clays and very fine silts, often passing into layers of fine brown sand. The lake stages are marked, on the contrary, by white or, more exactly, greenish clays, and form but a small portion of the thickness in the exposed sections. In this alternation of fluvial and lacustrine deposits the former comprise the bulk of the mechanical sediments, the latter the bulk of the fossils.

By seasonal changes in the water-level of interior seas there is an especial liability to the development of a broad intermediate zone, corresponding to that of the littoral bordering the open sea, and characterized by variegated shales showing mud-cracks, rain-prints, and ripple-marks. Thus in ancient interior basin deposits there may be shore relations indicated by the nature of the strata which might

[1] "Das Oxusproblem in historischer und geologischer Beleuchtung," *Petrographische Mitteilungen*, Vol. XLIV (1898), p. 211.

[2] *Explorations in Turkestan*, Carnegie Institution (1905), p. 25.

[3] *The Basin of Eastern Persia and Sistan*, Carnegie Institution (1905), Plate X, and p. 291.

readily be mistaken for those of an epicontinental sea in tidal connection with the ocean. As distinguishing features it may be noted that in the former case the subaqueous shore deposits take place continuously for months. The periods of exposure likewise endure for months, and the prolonged desiccation gives a maximum opportunity for the formation of mud-cracks and the hardening of rain-prints or foot-prints. This hardening is favorable to their preservation, as Lyell has shown, since the record is not readily washed out by the returning waters, which bring with them another layer of sediment, by which the record is buried and indefinitely preserved.[1]

The shores of the epicontinental sea, on the contrary, if open to the tides, are subject to two daily inundations, and the chances for the formation and preserval of mud-cracks is at a minimum, except at the highest limits of tidal flooding.

Variable water-level—marine deltas.—To consider the effects of irregular vertical movements upon deltas facing the ocean waters, it is to be noted that the change is due to movements of the land rather than of the sea. Of land movements the nature of subsidences is more difficult to observe than that of elevations. In the latter, successive beach-lines carved along coasts, successive development of partial peneplains, and the actual observations of uplifts, as those noted during the nineteenth century along the coast of Chili, all give testimony to the largely intermittent character of upheaval. But in regard to subsidences also, observations have been made. These are sometimes slow, and for a time at least equable, as that affecting the present eastern coast of the United States, at other times subsiding at unequal rates, as indicated by the halt during the past century of the subsidence of the deltas of the Rhine and the Meuse, compared with the occasionally disastrous inroads made during the previous millennium.[2] Again at times districts suddenly subside during earthquakes. Such movements must tend to occasionally flood considerable portions of the delta surfaces of large rivers with sea water, which will stand over the regions perhaps for centuries or millenniums before it is again reclaimed by delta-rebuilding.

Perhaps the most striking instance is to be found in the Runn of

[1] *Quarterly Journal of the Geological Society of London*, Vol. VII (1851), p. 239.

[2] A. de Lapparant, *Traité de géologie*, 4th ed., pp. 570, 572.

Cutch on the southern portion of the delta of the Indus, a brief account of which is given by Suess[1] after Cunningham, Wynne, and Burnes.

The Indus, at least since 680 A.D., has delivered the most of its water along the western side of its delta. On the extreme eastern side walled off from the sea by the hilly island of Cutch, is found the Runn of Cutch, a salt desert, estimated to comprise about 10,000 square miles in area. The great Chinese traveler Hwen Tsang, who visited it in the year 641 A. D., describes the district even at that time as low-lying and damp, and the ground as filled with salt. This immense plain of the Runn is covered, during a southwest monsoon from Lakhpat, with salt water; during the floods of the Indus with fresh water, conveyed by the channels of the Banas or the Luni; at other times it is dry, and is then strewn with great patches of salt of dazzling whiteness.

This region was visited in 1819 by a violent earthquake and a low mound called the Allah Bund, or "mound of God," was raised across the northern side. Wynne and Suess, however, in contradistinction to Burnes and Lyell, consider that the real movement was one of subsidence of the Runn, as indicated by the fact that eight years after the earthquake the Indus burst its banks in upper Sind, flowed across the Allah Bund, which thus offered no obstacle to its progress, and spread over the Runn of Cutch.

Without attempting to sharply discriminate between variable delta-building and variable subsidence in this disputed case, it remains as the most striking instance of how, for more than a thousand years, portions of a delta surface the major part of which is land may be covered by the sea. Here the alternation of fresh- and salt-water floods with seasons of aridity is not representative of pluvial climates, but depends upon, *first*, the small rainfall of the region; *second*, the southwest monsoon which raises the sea-level slightly during one season; and, *third*, the river floods produced by a period of rains in distant mountains.

Under more usual circumstances the reach of the ocean waters, which now spread periodically over the Runn, would doubtless be greatly diminished, since in the course of the six hours between high

[1] *Das Antlitz der Erde*, Eng. trans., Vol. I, pp 40–47.

and low tide the water could flow but a limited distance over tidal flats, and in a more pluvial climate much of the region would doubtless be covered with fresh-water lakes and lagoons. Both salt and fresh water, by wave- and current-action, would tend to differentiate the water from the land. This conclusion is in conformity with what is observed upon deltas facing the sea, the delta being normally divided into a land surface occasionally covered by river floods and a subaqueous portion perennially covered by the sea water, the two being separated by a relatively subordinate littoral zone.

CONCLUSIONS ON GENERAL NATURE OF DELTA DEPOSITS

A review of the deltas of the world at the present time shows that, as a rule, the shallow basins marginal to the continents are filled with alluvial deposits, except in regions where the submergence or warping is very recent, as in the case of the Baltic Sea and Hudson's Bay, or where tidal scour tends to maintain an open estuary.

The deltas of the larger rivers, where they have had a reasonable geological time to form, customarily end in deep water beyond the general limits of the coast-line.

But the present is a time of continental extension and mountain-building, though the late Tertiary was still more striking in this respect. Therefore it may be reasonably concluded that at times of similar topographic character in past geological history such epicontinental seas as remained became, as a rule, largely filled, and usually rather rapidly, by delta deposits, and shallow seas would thus give way to alluvial plains. Even in times of partial continental submergence, however, as in the upper Devonian and the Carboniferous, the mountain-building then present would be expected by the accompanying erosion to have given rise to extensive subaërial delta deposits, which could, however, have only occupied the landward portions of the broad epicontinental seas. Under such circumstances the preceding discussion has indicated that the beach might be a shifting line, usually fluctuating about a certain limit, but sometimes transgressing the alluvial delta plain, or again moving a shorter distance seaward. The strata, as seen in vertical section, would be, under these assumed conditions, to a considerable extent land deposits in the region of thick sedimentation, largely marine where they thinned

out on the seaward side. The two kinds of formation would be intimately interfingered at the contact—an interfingering which might extend for tens, or occasionally for hundreds, of miles.

The distinction, however, which it is wished to emphasize here is that these deposits would be chiefly either land or marine, and only subordinately littoral. The broad exposure of the land surface is not a matter of between tides. Limited districts, as the Runn of Cutch, might be regularly inundated by sea water during a certain portion of the year, and other districts might be occasionally covered by great storms; but more usually changes over considerable border districts from land to sea would be a matter of centuries at least. In interpreting such deposits, mud-cracks, rain-prints, foot-prints need not necessarily, nor even usually, indicate exposures of tidal mud-flats, as is usually assumed,[1] but may equally well be interpreted as records of a subaërial delta surface, regularly flooded by river inundations or occasionally by the sea. Again, an occasional intercalation of strata holding marine or estuarine fossils in a great series of mechanical sediments is not evidence in itself that the entire formation is marine or estuarine. On the other hand, an occasional occurrence of fresh-water strata in an unfossiliferous formation is not evidence in itself that the entire series is of continental origin.

In times when the lands are topographically old, it is to be anticipated that land surfaces upon delta deposits will be at a minimum since marine planation will not have been lessened in power; while, on the other hand, the ability of the rivers to build out against the seas, or to build up whenever subsidences occur, will have greatly diminished.

CONCLUSION ON PRESENT CONTINENTAL SEDIMENTATION

It has been shown in the preceding pages that important continental deposits either now in process of formation, or so recently made as still to exist as superficial formations, cover an appreciable portion of the continents.

Of these the interior formations of arid climates have been roughly estimated to cover a tenth of the land surface of the globe, the pied-

[1] The question of the origin and preserval of mud-cracks made on tidal flats is considered later.

mont waste slopes of several continents to cover an area of the same order of magnitude as that of the great mountains from which they come. Interior basins of pluvial climates are seen to be largely filled by fluviatile deposits; again, where the land meets the sea sediment is deposited as deltas, forming fluviatile deposits with bottoms far below the level of the sea. These have been observed to be of varying importance in different continents, and no estimate of their aggregate areal extent has been given. Still, it would seem to be in the neighborhood of the truth to place the subaërial deposits of piedmont waste, of continental basins, and of deltas as covering a tenth of the emerged continental surfaces. Adding this to the estimate of the deposits of arid climates would give a fifth of the land surface as mantled by continental formations. From the generalized profile showing the relative areas of the earth's crust at different heights given by Penck,[1] and also by Gilbert,[2] from Murray's figures it is seen that one-fifth of the land surface is elevated more than 1,200 meters above the sea. The more elevated portions of the crust suffer, *on the whole*, the most severe and rapid erosion. Consequently, a general idea of the localization and rapidity of erosion upon the land may be gained by stating that at present one-fifth is subject to extremely rapid erosion, one-fifth to rapid erosion, one-fifth to moderate erosion, one-fifth to slight erosion, and one-fifth, either now or in recent geological times, to sedimentation. Not all of the latter would be permanently preserved by the continued action of the forces which have led to their accumulation. Such superficial formations as those deposited upon slightly warped slopes previously graded, as the Lafayette formation of the eastern United States is presumed to be, or the thin deposits of ancient deserts, are especially liable to be destroyed, so that the geological record of former ages should show a far less proportion of thin and superficial land deposits. Basin deposits of either desert or pluvial climates and delta deposits possess, however, indefinite thickness, and the chances of indefinitely long preservation of at least the lower portions is nearly as good as in the case of the deposits upon the floors of epicontinental seas. As, however, changes in geological activities

[1] *Morphologie der Erdoberfläche*, Vol. I (1894), p. 136.

[2] "Continental Problems," *Bulletin of the Geological Society of America*, Vol. IV (1892), p. 180.

frequently take place by subsidence of land areas, even the highest of such land deposits stand a chance of preserval. Therefore others of a similar nature should be expected to occur buried in older portions of the geological record, but not so abundantly as those originally formed at lower levels. Continental deposits depend, however, so largely upon the climate and geography that their areal extent and importance must have varied largely through geological time.

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